AD-A114 136 MITRE CORP MCLEAN VA METREK DIV F/G 1/2
A COMPARISON OF FAA INTEGRATED NOISE MODEL FLIGHT PROFILES WITH--ETC(U)
DEC 81 G W FLATHERS DTFA01-82-C-10003
UNCLASSIFIED MTR-81W00288 DOT/FAA/EE-82/10 NL

1 of 1
AD
A114136

END
DATE
FILMED
5 82
DTIC

AD A114136

DOT/FAA/EE-82/10

Office of Environment
and Energy
Washington, D.C. 20590

# A Comparison of FAA Integrated Noise Model Flight Profiles with Profiles Observed at Seattle-Tacoma Airport

George W. Flathers, II

MTR-81W288

December 1981

Final Report

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.





U.S. Department of Transportation
Federal Aviation Administration

82 05 05 016

Technical Report Documentation Page

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| FAA-EE-82-10 | AD A114 136 | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| A Comparison of FAA Integrated Noise Model Flight Profiles with Profiles Observed at Seattle-Tacoma Airport | December 1981 |
| | 6. Performing Organization Code: W-47 |
| 7. Author(s): George W. Flathers, II | 8. Performing Organization Report No.: MTR-81W00288 |
| 9. Performing Organization Name and Address: The MITRE Corporation, 1820 Dolley Madison Boulevard, McLean, Virginia 22102 | 10. Work Unit No. (TRAIS) |
| | 11. Contract or Grant No.: DTFA01-82-C10003 |
| 12. Sponsoring Agency Name and Address: Department of Transportation, Federal Aviation Administration, Office of Environment and Energy, Washington, D.C. 20591 | 13. Type of Report and Period Covered |
| | 14. Sponsoring Agency Code: DOT/FAA |

15. Supplementary Notes

16. Abstract

The Federal Aviation Administration's Integrated Noise Model (INM) is a series of computer programs designed to estimate environmental noise levels in the vicinity of an airport. As part of MITRE's efforts to validate INM computations for the FAA, a comparison was made between arrival and departure profiles contained in the INM data base and those observed in actual operations at the Seattle-Tacoma International Airport. ARTS-III radar data were used to determine actual altitude and velocities of aircraft at various distances from the runway during arrival and departure operations. This report presents the results of the comparison.

| 17. Key Words | 18. Distribution Statement |
|---|---|
| flight profile<br>validation<br>statistical comparison | Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151 |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 63 | |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

# A Comparison of FAA Integrated Noise Model Flight Profiles with Profiles Observed at Seattle-Tacoma Airport

George W. Flathers, II

December 1981

MTR-81W288

SPONSOR: Office of Environment and Energy
CONTRACT NO.: DTFA01-82-C10003
PROJECT NO.: 1494A
DEPT.: W-47



The MITRE Corporation
Metrek Divison
1820 Dolley Madison Boulevard
McLean, Virginia 22102

## EXECUTIVE SUMMARY

The Federal Aviation Administration's Integrated Noise Model (INM) is a series of computer programs designed to assess the noise impact of aircraft operations in the vicinity of an airport. The user of the INM supplies data concerning the airport and runway layout, the number and types of aircraft, and description of the flight tracks they use. The INM computes and reveals the noise environment in terms of preselected noise metrics of the user's choice. As part of MITRE's overall effort to check the validity of the results of INM computations for the FAA, a comparison was made between the arrival and departure profiles contained in the INM data base and those observed in actual operations at the Seattle-Tacoma International Airport. A flight profile describes aircraft altitude and velocity as a function of distance from the runway during a takeoff or an approach to landing. The extensive data base in which the INM profiles are stored also contains noise and other performance data for various types of aircraft.

In the spring and summer of 1979, MITRE conducted a similar flight profile study which is presented in MTR-80W00119, "Comparison of FAA INM Flight Profiles with Observed Altitudes and Velocities at Dulles Airport," Reference 1. The main conclusion of that study was that, for departure operations, most airlines were using procedures which differed significantly from those assumed by the then-current Number 7 INM data base. Due to the sparsity of data sampling locations and limitations in the data collection mechanisms, however, the exact nature of observed departure profiles could not be determined. Since the time of the Dulles study, the FAA has prepared a new data base (Number 8) which includes revisions based on a relatively recent FAA Advisory Circular (AC91-53, Reference 2) outlining recommended standard noise abatement departure procedures. The comparisons in the present study are made with respect to the Number 8 INM data base.

### Methodology

The basic approach taken in this study is an extension and a refinement of that taken in Reference 1. ARTS-III radar data provided the raw information upon which statistical inferences could be made about actual flight operations. Using the target reports provided by the ARTS-III system, and a special smoothing technique called cubic spline function smoothing, the altitude and velocity of each aircraft on arrival or departure was determined over several

points within 10 nautical miles of the airport. The altitudes and velocities of nearly 3000 arriving or departing aircraft were determined in this manner from data collected in the period between May and July, 1981.

This large sample was aggregated into smaller samples according to the type of operation conducted (namely, arrival or departure) and the type of aircraft involved. In this study, sample sizes were large enough to permit investigation of the following six aircraft types: DC-9, B-737, B-727, DC-10, L-1011, and B-747. Profiles for each type of aircraft were characterized statistically and compared directly with appropriate profiles taken from the Number 8 INM data base.

Results for Arrivals

The INM approach profile for standard air carrier arrivals depicts a continuous vertical decent along a $3^{\circ}$ glide slope to the point of touchdown approximately 1000 feet beyond the runway threshold. The speed of the aircraft within 10 nautical miles of the runway is assumed to be constant at the INM supplied final approach speed. When compared to this profile, the following trends were noted:

- Observed altitude profiles suggested that all six types of aircraft closely follow the $3^{\circ}$ glide slope. The usual sources of descent guidance for an air carrier pilot on an approach to landing are the Instrument Landing System (ILS) glide slope, or an optical aid called the Visual Approach Slope Indicator (VASI), both of which provide an approximately $3^{\circ}$ glide slope. Observed altitudes varied around the glide slope as a function of distance from the runway: as aircraft approached the runway, variations in observed altitude became progressively smaller and more centrally distributed about the $3^{\circ}$ glide slope.

- Observed velocity profiles revealed that most aircraft were performing a decelerating approach rather than one of constant speed. Most aircraft approached the airport area at a significantly higher speed but slowed to within a few knots of the INM designated final approach speed as they came within 2 nautical miles of the runway. The frequent occurrence of the decelerating approach is consistent with the predominant conditions at Seattle: VFR weather and fairly light traffic, both of which make decelerating approaches practical.

## Results for Departures

There are many other factors associated with departures which contribute to considerably more variation in observed operations. There are procedural differences in the way the departures are performed by various airlines. In addition, there are performance-limiting factors such as aircraft weight, pressure altitude, temperature, and wind which introduce additional sources of variation. Accordingly, a more detailed analysis of departures was performed.

All airlines specify their own standard departure procedures in their flight operations manuals. These procedures are usually fashioned after the FAA suggested noise abatement departure profile, (as outlined in FAA Advisory Circular 91-53, Reference 2), with various levels of compliance. The profiles of most airlines resemble each other for aircraft with high bypass ratio engines. For low bypass ratio engines, however, the FAA procedure specifies a greater thrust reduction after takeoff than some airlines use. This would result in a steeper climb angle than under the FAA procedure, with all other factors held equal.

The INM data base, on the other hand, has a set of completely defined profiles for each aircraft type which were constructed under the assumption that the FAA procedure is being followed by all aircraft. In addition, the data base has up to seven slightly different profiles for each aircraft type to reflect differences in departure performance attributable to varying departure weights. Under the assumption that aircraft departure weight and stage-length (the non-stop fight distance) are proportional, the INM estimates departure weight by using stage-length as an index. The profile for the most likely stage-length was used as the INM baseline for the comparisons and the following results were noted:

- Observed altitude profiles for the DC-9 and B-737 were much lower than the INM profiles for the near field segment (the portion of the departure within 3 nautical miles of the Brake Release Point (BRP)). There was fairly close agreement between observed and INM profiles for the other aircraft in the near field segment. For the far field segment (the portion further than 3 n.m. from BRP) the DC-9 and B-727 were much higher than the INM profiles. A possible reason for this observation is that the procedures used by the pilots of these two aircraft types are not fashioned after the FAA profile which the INM assumes.

- Observed velocity profiles were within reasonable agreement with INM profiles for the near field segment for all six types of aircraft. For the far field segment all observed velocity profiles were close to the INM profiles, with the exception of the B-727 which was faster than the INM profile.

- An analysis of observed B-727 departures was performed to determine if differences in departure procedures of different airlines have observable effects on actual departure performance. The median B-727 departures of five major airlines were compared with each other. No real differences were observed in altitude profiles of the five airlines for the departure segment within 5 n.m. from BRP. Beyond this point, however, the disparity became more distinct. At 8.5 n.m. from BRP the highest median departure was approximately 1000 feet higher than the lowest. There were no tangible differences in the velocity profiles for the entire departure. A review of available flight operations material revealed that the airline with the lowest median altitude at 8.5 n.m. also employs a sharp thrust cut-back which was ultimately intended by FAA AC91-53. The expected and observed result of this cut-back was the shallower climb angle.

- To measure the sensitivity of both observed and INM profiles to differences in stage-length, an analysis was performed on B-727 departures grouped into four different stage-lengths. It was found that slight but palpable differences exist in both INM and observed profiles due to stage-lengths. However, variation from other sources is several times greater than the sensitivity of the INM to changes in stage-length.

- Based on the findings of this study, the FAA Office of Energy and Environment proposed a few revisions to the Version 8 INM departure profiles for the DC-9, B-737, and B-727. The revised profiles were the result of recomputing departure performance based on the departure procedures which were evidently in use by pilots of these aircraft. The agreement of observed profiles with the revised Version 8 profiles was found to be significantly improved.

## Conclusions and Recommendations

This profile study represents the most comprehensive comparison made to date between observed operations and profiles contained in the INM data base. In general, the new Number 8 profiles have significantly improved observed-INM profile agreement. Because the version of the INM which implements the Number 8 data base had not yet been released, the sensitivity of noise estimates to differences in flight profiles was not investigated. This sensitivity should be quantified in a future effort. However, it is anticipated that improvements in the flight profiles will, in most instances, result in more accurate noise estimates. Major observations, and recommendations to make the INM easier to use and to improve the accuracy of results, are listed below:

- For arrivals, the agreement between observed operations and likely INM profiles was generally good. Observed arrivals for all six types of aircraft followed the $3^{\circ}$ glide slope and exhibited decelerating approaches

- At present, the Number 8 data base contains predefined approach profiles which describe approaches of constant speed for the last 10 nautical miles before touchdown. The predictable patterns of observed arrivals at Seattle-Tacoma suggest that inclusion of a decelerating profile in the data base may also be of benefit to the user, especially at locations where weather and traffic conditions make decelerating approaches popular.

- For departures, observed-INM profile agreement was good for aircraft with high bypass ratio engines, but the agreement was not as good for low bypass ratio engines. The disparity for the case of low bypass ratio engines was attributed to differences between assumptions under which the INM profiles were constructed and actual operating practices used by various airlines. This hypothesis was supported by the analysis of B-727 departures grouped according to airline which indicated that differences in observed profiles could be traced to procedural differences. The revised INM profiles for the DC-9, B-737, and B-727 proposed by the FAA result in significantly improved agreement with observed profiles, and they should be incorporated as a permanent part of the INM data base.

- The analysis of B-727 departures grouped according to stage-length revealed that differences between INM profiles for the shortest and longest stage-length tend to be masked by variation from other sources. In addition, the assumption that weight estimation can be based on stage-length may not always be true. Based on these findings the number of stage-length categories should be reduced from a maximum of seven to a maximum of two or three.

## TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

## LIST OF ILLUSTRATIONS
(Concluded)

# 1. INTRODUCTION

The Federal Aviation Administration's Integrated Noise Model is a series of computer programs designed to forecast the noise environment in the vicinity of an airport. The user of the INM supplies data concerning the airport and runway layout, the number and types of aircraft, and the flight tracks they use. The INM computes and reveals the noise environment in terms of preselected noise metrics. As part of MITRE's efforts to check the validity of the results of INM computations for the FAA, this report describes a comparison made between arrival and departure profiles contained in the INM data base and those observed in actual field operations at the Seattle-Tacoma International Airport. A flight profile describes aircraft altitude and velocity as a function of the distance from the runway. MITRE is also involved in the validation of other aspects of the INM, including noise versus distance relationships, which will be documented in a subsequent report.

## 1.1 Background

In the course of calculating noise exposure in the vicinity of an airport, the INM performs four primary functions. It first estimates the noise generated at the source (the aircraft engine). Secondly, it estimates the distance from the source to the receiver (at some point on the ground). It then computes the losses and other adjustments to noise as it travels from the source to the receiver. In the fourth and final function it compounds the effects of multiple aircraft operations to provide a time-based environmental noise descriptor or metric. In performing these functions the INM uses data supplied by the user, several theoretical noise relationships, and its own extensive data base containing noise data and flight profile data for various types of aircraft.

The focal point of this study was the flight profile section of the INM data base. The specific objective was to determine the level of agreement or disagreement between the profiles contained in the data base and those observed in actual operations within a 10 nautical mile distance from the airport. This study was performed in conjunction with other aspects of MITRE's INM validation efforts based on data collected at the Seattle-Tacoma International Airport. Because the version of the INM which implements the Number 8 data base had not yet been released, the sensitivity of noise estimates to differences in flight profiles was not investigated.

## 1.2 Previous Research

In the spring and summer of 1979, MITRE conducted a similar flight profile comparison study which is presented in MTR-80W00119, "Comparison of FAA INM Flight Profiles with Observed Altitudes and Velocities at Dulles Airport," (FAA Report No. FAA-EE-80-4), Reference 1. In that report, comparisons were made using the then-current Number 7 INM data base profiles. The main conclusion of the study was that, for departure operations, most of the airlines were using procedures which differed significantly from those assumed by the INM. Due to the sparsity of data sampling locations and limitations in the data collection and processing mechanisms, however, the exact nature of the observed departure profiles could not be determined. For arrival operations, some differences were noted between INM profiles and observed profiles, but the magnitude of the differences was much less than for the case of departures.

Since the time of the Dulles profile study mentioned above, the FAA has prepared a new data base (Number 8) with updated arrival and departure profiles for most types of aircraft. The new profiles include revisions based on a relatively recent FAA Advisory Circular (AC91-53, Reference 2) outlining recommended standard noise abatement departure procedures. The comparisons in the present study are made with respect to the Number 8 INM data base.

## 2. METHODOLOGY

The basic approach taken in the current study is an extension and refinement of the approach described in Reference 1. ARTS-III radar data recorded at the Seattle-Tacoma Airport provided the raw information upon which statistical inferences could be made about actual flight operations. Appropriate profiles taken from the Number 8 INM data base were used as the baselines for the comparisons. This section gives a brief description of the operating environment at Seattle and the processing of raw radar data to determine aircraft altitude and velocity at specified distances from the runway. A more complete description of the analytical techniques used in the data processing is given in Appendix A.

The Seattle-Tacoma Airport was selected for the collection of actual operations data because of three favorable characteristics: first, it had an established noise monitoring system which was essential to other tasks in the INM validation effort; second, it had an appropriate mix of air traffic in terms of aircraft types and stage-lengths (the non-stop flight distances); and third, the arrival and departure policies of local airport authorities did not interfere or conflict with the standard operating practices of most airlines. A diagram of Seattle-Tacoma Airport is given in Figure 2-1.

### 2.1 Data Processing Overview

The raw data used in the profile analysis came from Seattle-Tacoma in the form of ARTS-III radar extractor tapes. The data contained on each tape included, among other things, radar target reports and interfacility flight plan messages. A target report was generated for each instance when an aircraft's position was determined based on its response to a Mode A interrogation from the ATC Radar Beacon System (ATCRBS) and its altitude was reported in response to a Mode C interrogation. The aircraft's position was recorded in the target report in terms of range from the radar antenna and the bearing to the aircraft with respect to Magnetic North. Updated target reports containing revised position and altitude data were generally available for each scan of the radar, or approximately every 4.7 seconds. A flight plan message was recorded on tape for each IFR flight which was about to enter the airspace under the jurisdiction of the Seattle Terminal Radar Control Facility. These messages contained the aircraft identification, aircraft type, proposed operation, and other supporting data about the flight.

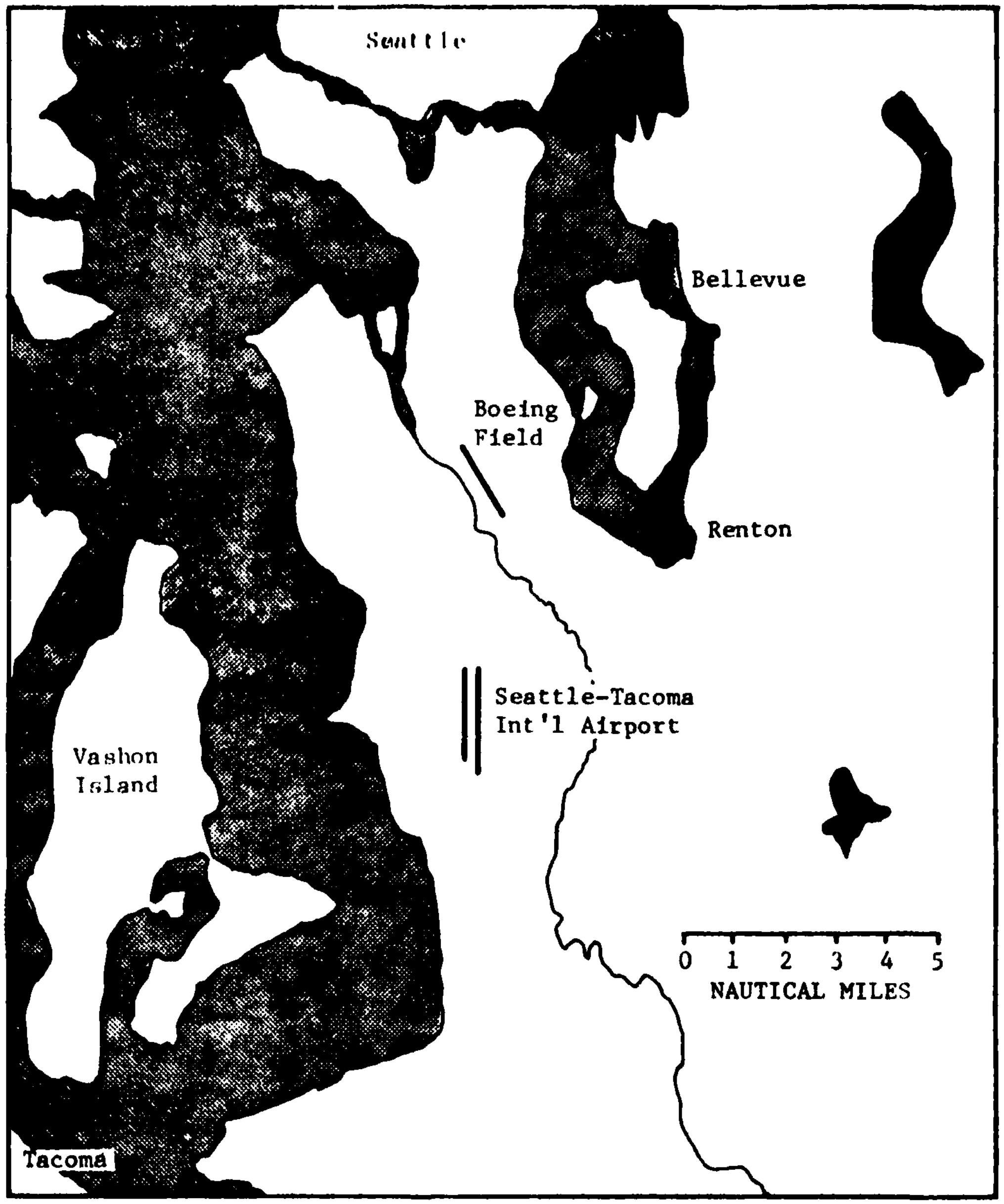



**FIGURE 2-1**
**THE SEATTLE-TACOMA INTERNATIONAL AIRPORT**

Target reports and interfacility flight plan messages were extracted from the radar tapes by means of a MITRE developed computer program called ARTS81. Once extracted, these two blocks of data were then submitted to another program, SMOOTH, which was designed to process the Seattle data. In the latter program, a unique flight plan message was assigned to each track, or string, of target reports from an aircraft departing or approaching Seattle. In this way, the identity and type of airplane could be established for each track of target reports.

Because individual target data are subject to errors, a smoothing operation was performed before estimating altitude and velocity. A description of the method used in this study, cubic spline function smoothing, is offered in Appendix A. The end result of the smoothing process was a set of three cubic equations which described the position of the aircraft as a function of time. In analytical terms, the three functions were X(t), which described lateral displacement from the extended runway centerline, Y(t), which described longitudinal displacement from an arbitrary point on the runway, and Z(t), which described the aircraft's height above the runway surface. Once X(t) and Y(t) were known, it was a simple matter to determine absolute velocity at a particular time by taking the first derivative of those two functions to find the velocity vector in each direction. Vector addition was then performed to find actual absolute velocity.

## 2.2 Sampling Stations and Lateral Boundaries for Aircraft Flyovers

It was determined that an adequate representation of the velocity and altitude profiles could be made by considering each aircraft flyover at strategically located "sampling stations". A sampling station was simply a longitudinal position located with respect to the runway. Eight sampling stations were used for departures and arrivals, thereby permitting a detailed view of flight profiles over a much greater distance than previously available. For departures, sampling stations were positioned at a point 1.5 nautical miles (NM) from the point where the take-off roll commenced (the Brake Release Point (BRP)), and at 1 NM intervals thereafter to 8.5 NM from BRP. For arrivals, sampling stations were positioned one-half nautical mile from the threshold of the runway, and at 1 NM intervals before that to 7.5 NM from the threshold. A diagram of sampling station location for both arrivals and departures is given in Figure 2.2.

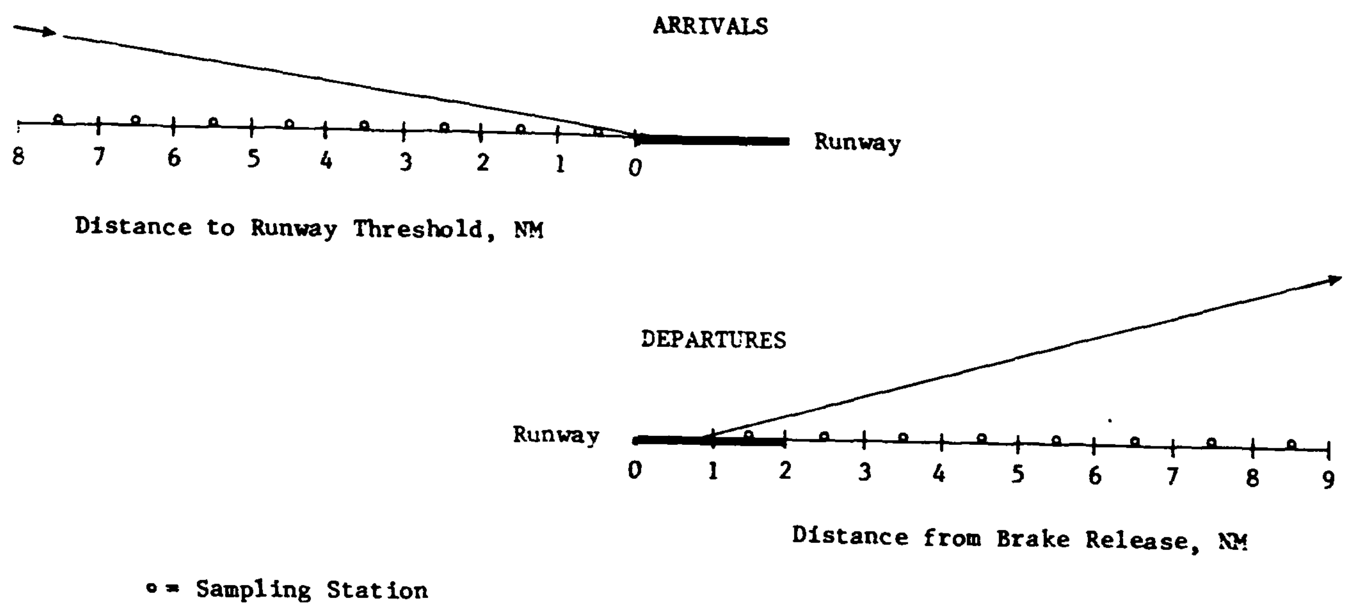



**FIGURE 2-2**
**POSITIONS OF SAMPLING STATIONS FOR ARRIVALS AND DEPARTURES**

As an aircraft passed over a sampling station on its departure or its approach to landing, the time of the closest point of approach (CPA) to the sampling station was determined. The CPA was merely the point at which the aircraft was directly over the sampling station. The time of CPA was determined using linear interpolation on the raw target data. Altitude and velocity were then determined at the time of the CPA.

Lateral boundaries, as shown in Figure 2-3, were established around the runway centerline to eliminate from consideration the portion of those operations which involved turns shortly after departure or shortly before landing. Such turns affect aircraft performance and consequently distort the resulting flight profiles. As evident in Figure 2-3, however, which also shows the distribution of aircraft ground tracks for a typical day at Seattle-Tacoma, these "turning operations" were a small percentage of the total number of operations.

Radar data for eleven typical days of operations at Seattle-Tacoma were processed in the manner mentioned above. The eleven days occurred within the period May to July, 1981. Operations were extracted for an average period of 18 hours per day, usually from 0600 to 2400 hours local time. The weather for the 11 days included some brief periods of IFR conditions and winds were predominantly light. Table 2-1 shows the total number of operations extracted from tape and smoothed, and also provides a breakdown of the operations according to aircraft type. Because a disproportionate share of arrivals occured during the portion of the day when radar data was being extracted and processed, the number of departures does not equal the number of arrivals.

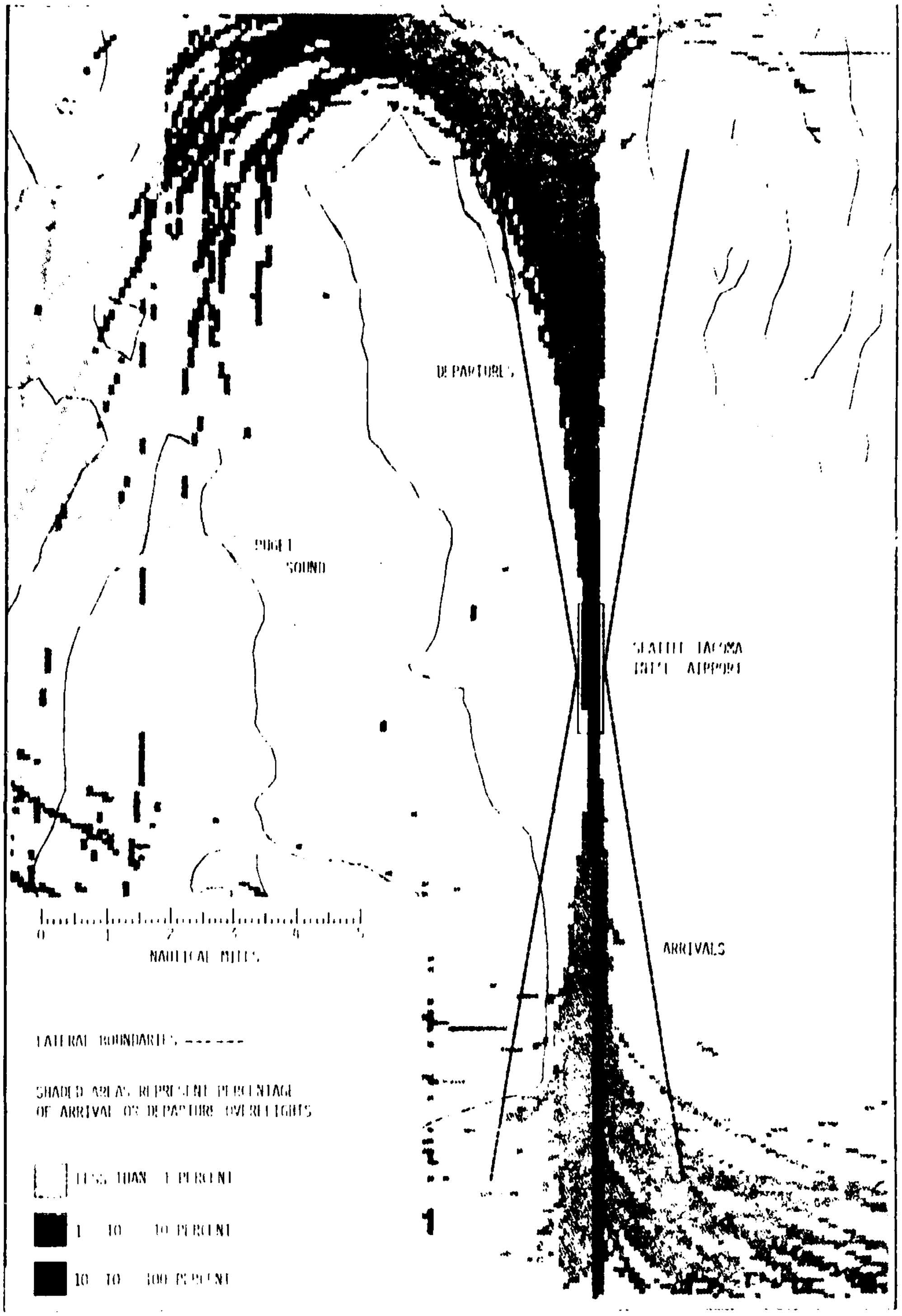



**FIGURE 2-3**
**LOCATION OF LATERAL BOUNDARIES AND DISTRIBUTION OF GROUND TRACKS FOR TYPICAL DAY**

TABLE 2-1
TOTAL NUMBER OF OBSERVED ARRIVALS AND DEPARTURES
BY AIRCRAFT TYPE

| Aircraft Type | Number of Arrivals | Number of Departures |
|---|---|---|
| Boeing 727 | 671 | 567 |
| Boeing 737 | 122 | 111 |
| Boeing 747 | 47 | 26 |
| McDonnel Douglas DC-9 | 167 | 130 |
| McDonnel Douglas DC-10 | 156 | 152 |
| Lockheed L-1011 | 49 | 42 |
| Other | 379 | 345 |
| Total | 1585 | 1373 |

## 3. ANALYSIS OF ARRIVALS AND RESULTS

Once the radar data had been extracted and processed to yield flight profile data, the profile data were used in a series of statistical tests to determine the nature of actual flight operations. The analysis of flight profiles was divided into two operational sectors: arrivals and departures. This section describes some supporting information on arrival procedures employed by the airlines, assumptions on arrivals made by the INM profiles, and briefly reviews the statistical techniques used to characterize the observed data.

### 3.1 Common Operating Practices for Arrivals

To gain a feeling of the operational issues confronting air carrier pilots on an approach to landing, the Flight Operations Manuals (FOM) of several airlines were reviewed. It was found that the arrival procedures of most airlines were very similar with respect to each other. The variables which determine the manner in which approaches are to be flown are weight, prevailing weather conditions, and the type of navigational guidance used (e.g., visual approach, ILS, or other instrument approach).

Landing approach speeds are based on weight and flap configuration, and can be determined by the flight crew for a specific case by reference to a table of values in the flight manual. Vertical profile or decent guidance is usually provided by reference to the electronic glide slope of the ILS, or optically by reference to a Visual Approach Slope Indictor (VASI). Both sources of decent guidance provide an approximately $3^{\circ}$ glide slope.

For operations conducted in marginal weather (low ceilings and visibility) where an ILS glide slope is being used, pilots are instructed to stabilize the aircraft on the approach at a point about 3 to 4 miles from the landing threshold. An aircraft is stabilized when it is established on the extended runway centerline and the glide slope, at its designated approach speed, and when only minor adjustments are necessary to remain within acceptable limits. Under average conditions pilots are usually able to maintain speed within  10 knots of the designated approach speed and maintain the glide slope to within  100 feet.

For approach operations conducted in visual weather conditions, pilots are given more latitude concerning speed management, although a $3^{o}$ glide path is still followed by reference to a VASI or ILS glide slope. Under better weather conditions, pilots can wait until they are about one-half mile from the runway threshold before establishing the designated approach speed. The tendency for air carrier pilots, given more freedom in the management of airspeed, is to approach the airport area at a significantly higher speed and gradually reduce speed so as to arrive at one-half mile from the runway at the designated approach speed. These "decelerating" approaches enable aircraft to land sooner while still remaining within safe operating limits at the point of touchdown. Even in ideal weather conditions, however, heavy air traffic conditions may constrain the speed management styles of pilots. Such constraints may come in the form of speed restrictions by ATC for the purposes of separating and sequencing air traffic.

## 3.2 INM Approach Profiles

The Number 8 INM data base includes standard approach profiles for three general classes of aircraft: commercial turbojet, general aviation, and military. The standard profiles continuously describe aircraft velocity, altitude, and thrust setting for the last 19 nautical miles of each landing approach. The only differences among the standard profiles for the three classes of aircraft are in approach speeds and thrust management. All the INM approach profiles used in this comparison come from the standard commercial jet class of approach profile which is described below.

Each of the three classes of approach profiles depicts a continuous vertical decent on a $3^{o}$ glide slope from the point where aircraft first enters the area to the runway surface. Like the actual glide slopes provided by aids such as a VASI or ILS, the INM approach profile glide slope usually intersects the runway surface at a point about 1000 feet beyond the runway threshold. This results in a threshold crossing height of 50 to 60 feet. The INM assumes each aircraft touches down at the glide slope-runway intersection, at which point each aircraft continues a roll-out using standard braking techniques.

The INM velocity profile for standard commercial jet approaches include one speed transition at a point nearly 10 nautical miles from the threshold. All commercial jet aircraft initially approach the area at 'terminal speed," which is maintained until

approximately 10 nautical miles from the threshold. At that point, speed is reduced to the unique final approach speed for that aircraft type. The terminal speed is usually the maximum authorized indicated airspeed for operations conducted under 10,000 feet Mean Sea Level (MSL), which is 250 knots. The final approach speed is a computed speed for each type of aircraft within the class, and is based on a nominal weight and flap configuration. The last 10 nautical miles of the INM approach are made in a "stabilized" state, i.e., the aircraft is established on the glide slope and maintains a constant speed to the point of touchdown. The roll out distance used in braking the aircraft after touchdown is based on aircraft arrival weight and final approach speed.

The inclusion of standard approach profiles in the Number 8 INM data base represents a significant improvement over older versions of the data base. Prior versions did not have completely predefined approach profiles and required the user to provide his own profiles based on what he believed were common operating practices. Even though the Number 8 data base specifies all aspects of a standard approach, the user is still given the flexibility of modifying a standard profile, or completely designing one of his own.

## 3.3 Statistical Issues and Graphic Presentation of Statistics

Operations that were extracted and processed were first broken down into two groups according to the type of operation conducted, namely, arrival or departure. Each group was then further aggregated into samples of aircraft operations at each sampling station according to aircraft type. These samples were the subject of a series of statistical measurements from which actual operations could be characterized. The following discussion, which is equally applicable to arrivals or departures, makes reference to Figure 3-1. This figure shows a "box-and-whisker" plot which provides a graphic presentation of the computed statistics for altitude and velocity at each sampling station.

The dark shaded box in Figure 3-1 encloses the 95% confidence interval for the mean of the population. The mean is the arithmetic average of the population. The confidence interval expresses the range within which the population mean is likely to exist. The 95% confidence interval, then, specifies an interval constructed in such a way that the population mean is expected to lie within it for 95 out of 100 similarly drawn samples. The confidence interval is constructed on the assumption that the underlying distribution of the population is a normal distribution.

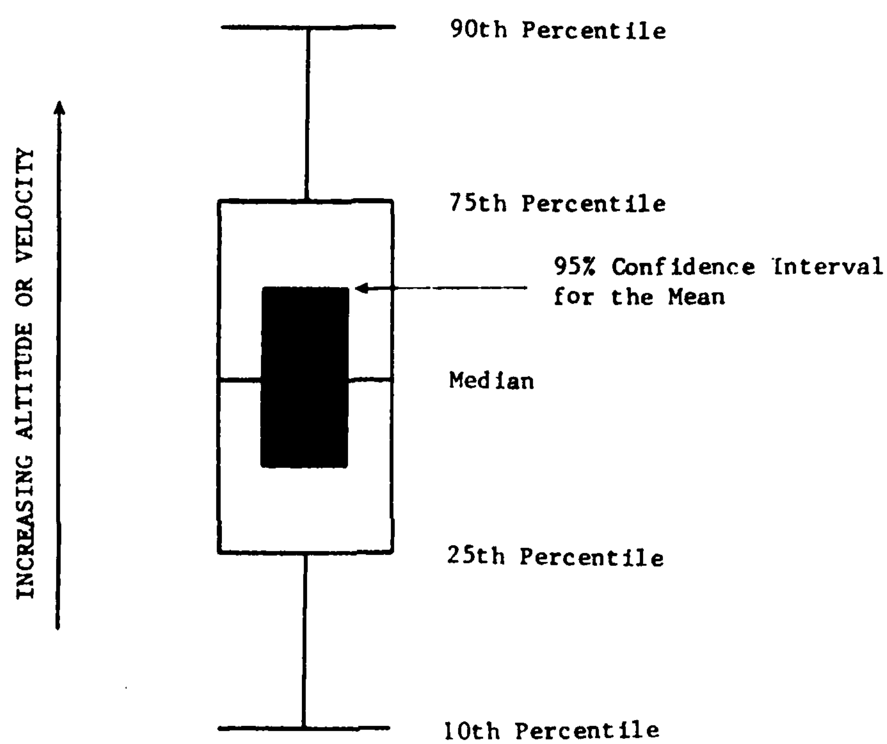



**FIGURE 3-1**
**BOX-AND-WHISKER PLOT FOR THE GRAPHIC REPRESENTATION OF COMPUTED STATISTICS FOR OBSERVED ALTITUDES AND VELOCITIES**

Another method used to characterize sampled data involves the use of nonparametric, rank-order statistics. The use of such statistics provides a simple view of sample distributions and requires no assumption about the underlying distribution of the population from which the sample was taken. In the box-and-whisker diagram of Figure 3-1, the 90th 75th, 25th, 10th percentiles, and the median are given.

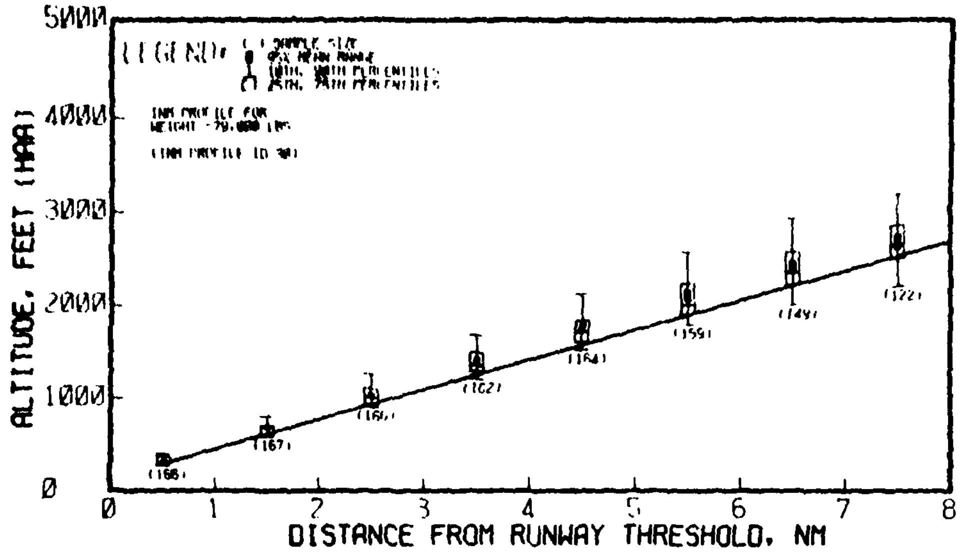
Rank-order statistics are based on the ordering of the sampled values from highest to lowest. The median, or 50th percentile, represents the value above which and below which lie one half of the sampled values. The 90th percentile represents the value above which is 10 percent of the sampled values and below which is 90 percent. Similar definitions apply to the other percentiles given in the box-and-whisker plot. A close spacing of these values indicates the population values are concentrated, or closely spaced. Conversely, wider spacing indicates the population values are more widely spread.

### 3.4 Results of INM - Observed Approach Profile Comparison

Figures 3-2 to 3-7 on the next few pages show the comparison of observed profile data to INM profiles for six aircraft types. In each case the INM profile selected for the comparison represents the most likely aircraft model for each type of aircraft observed at Seattle. The INM profile is depicted by the solid black lines. Statistics for the observed altitudes and velocities of each aircraft type are provided in the form of a box-and-whisker plots over each sampling station.

From visual inspection of the altitude profiles for each aircraft type, it is evident that all six aircraft types closely followed the $3^{o}$ glide slope (depicted by the INM) with only minor variations around it. Variations in observed altitudes behaved as a function of distance from the runway: as aircraft approached the runway, variations in observed altitude became progressively smaller (as evidenced by the compression of the box-and-whisker plots) and more centrally gathered around the INM $3^{o}$ glide slope.

A visual inspection of the velocity profiles reveals a somewhat different story. As aircraft initially approached the runway,



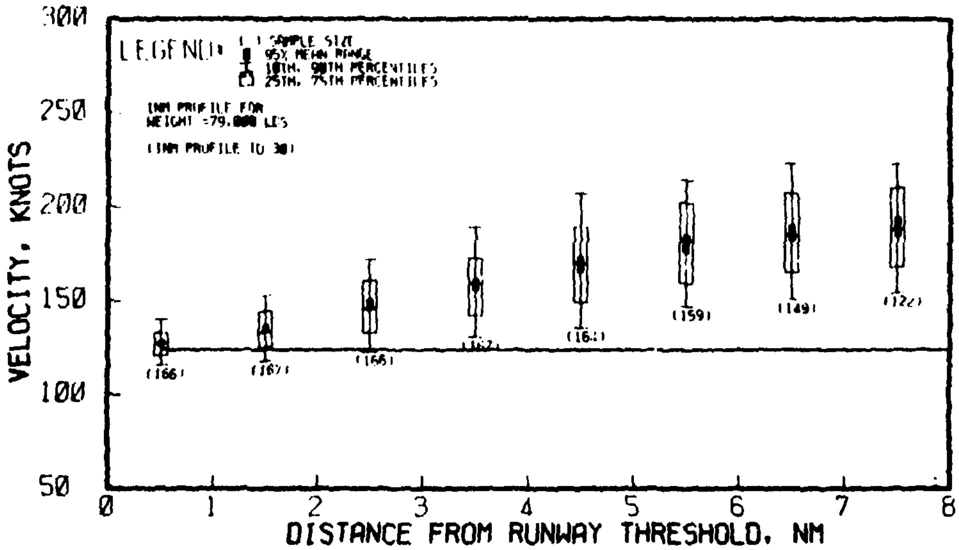
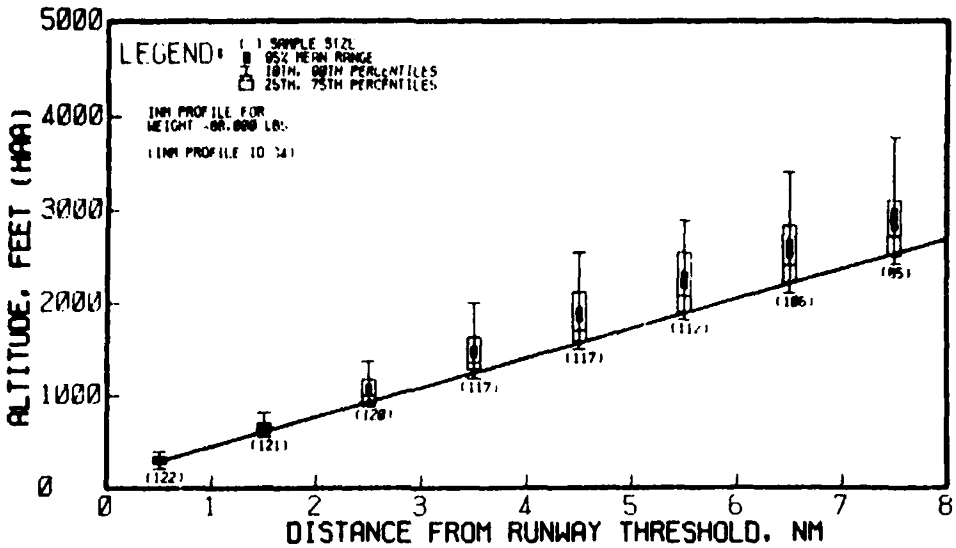




**FIGURE 3-2**
**OBSERVED AND INM PROFILES FOR DC-9 ARRIVALS**
**AT SEATTLE-TACOMA AIRPORT**



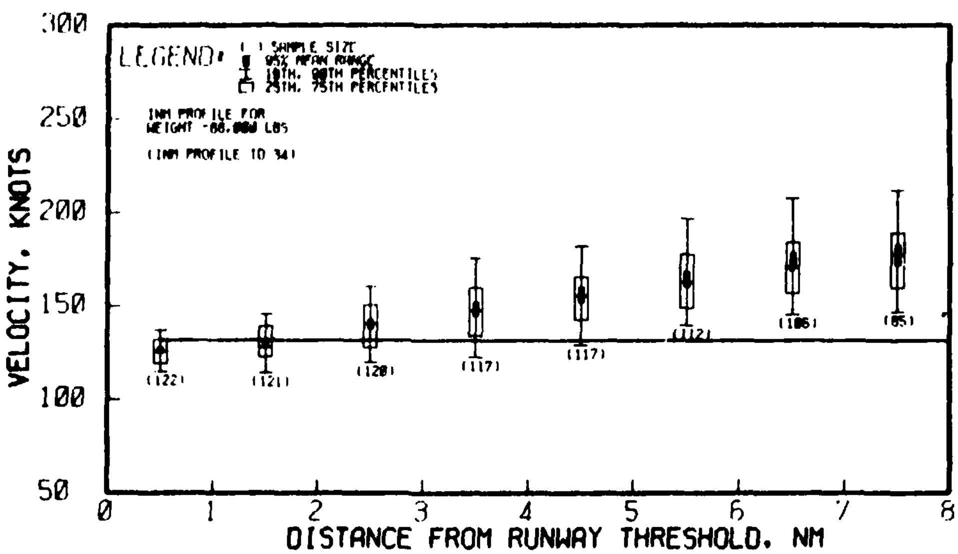
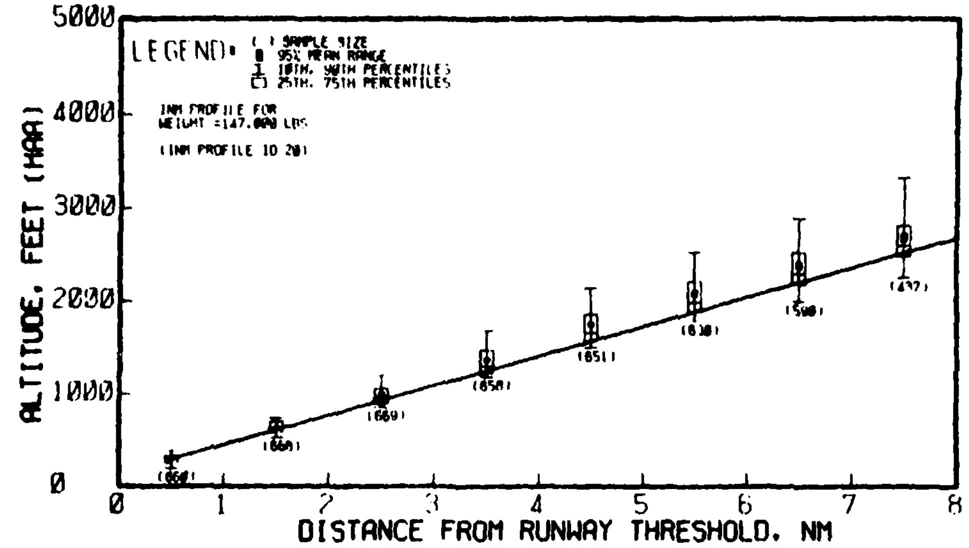




**FIGURE 3-3**
**OBSERVED AND INM PROFILES FOR B-737 ARRIVALS**
**AT SEATTLE-TACOMA AIRPORT**



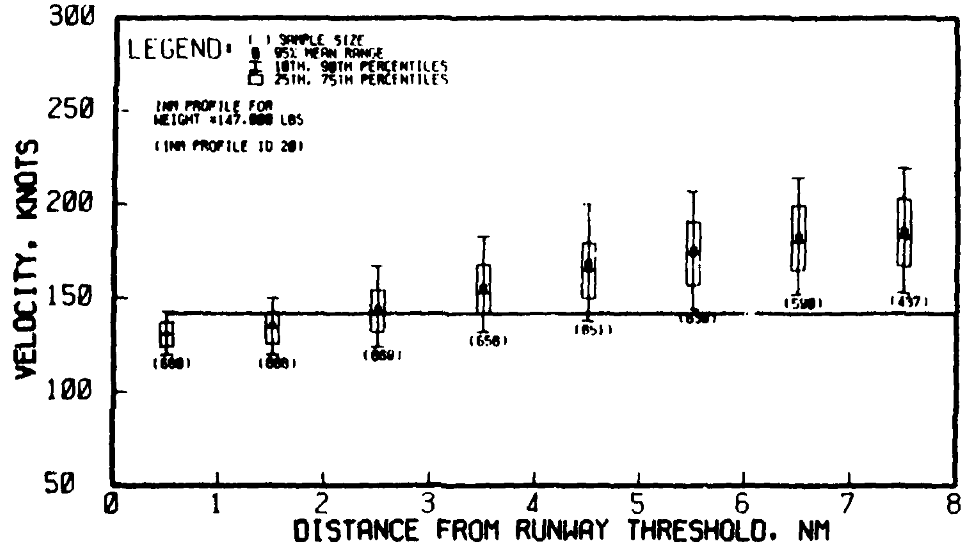
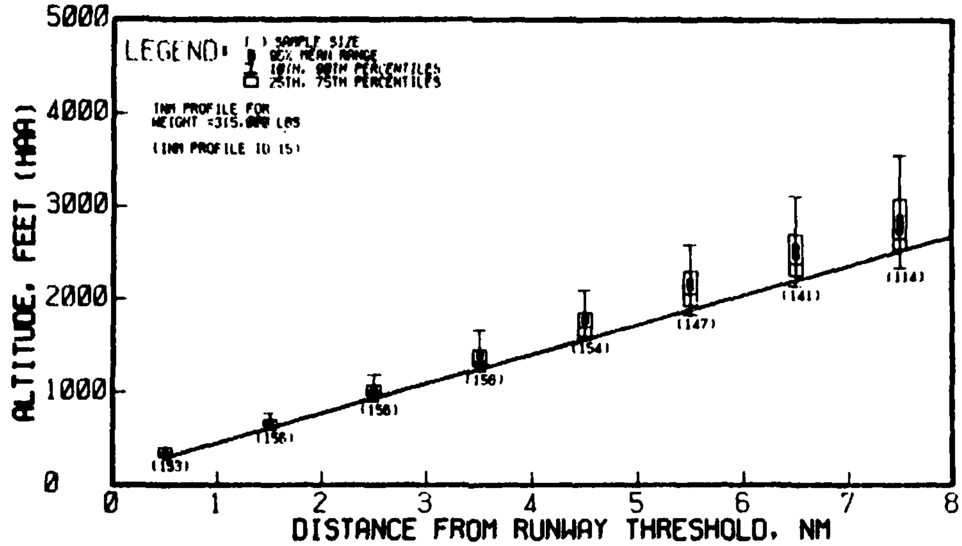




**FIGURE 3-4**
**OBSERVED AND INM PROFILES FOR B-727 ARRIVALS AT SEATTLE-TACOMA AIRPORT**



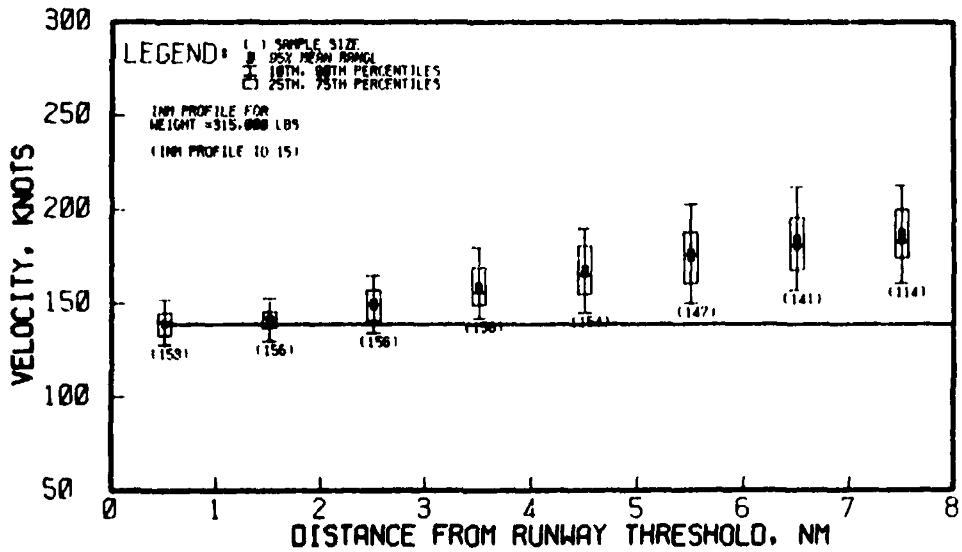




**FIGURE 3-5**
**OBSERVED AND INM PROFILES FOR DC-10 ARRIVALS AT SEATTLE-TACOMA AIRPORT**

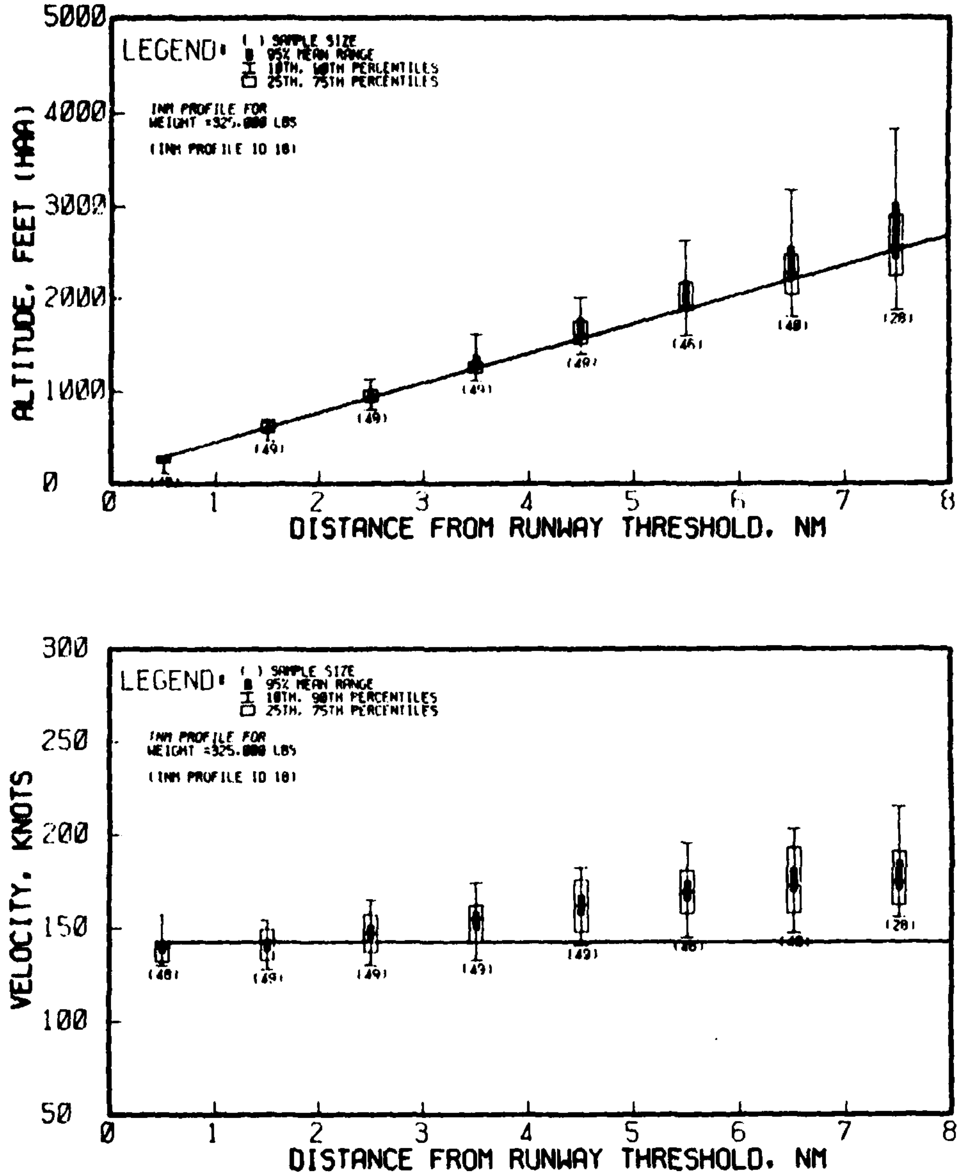



**FIGURE 3-6**
**OBSERVED AND INM PROFILES FOR L-1011 ARRIVALS AT SEATTLE-TACOMA AIRPORT**

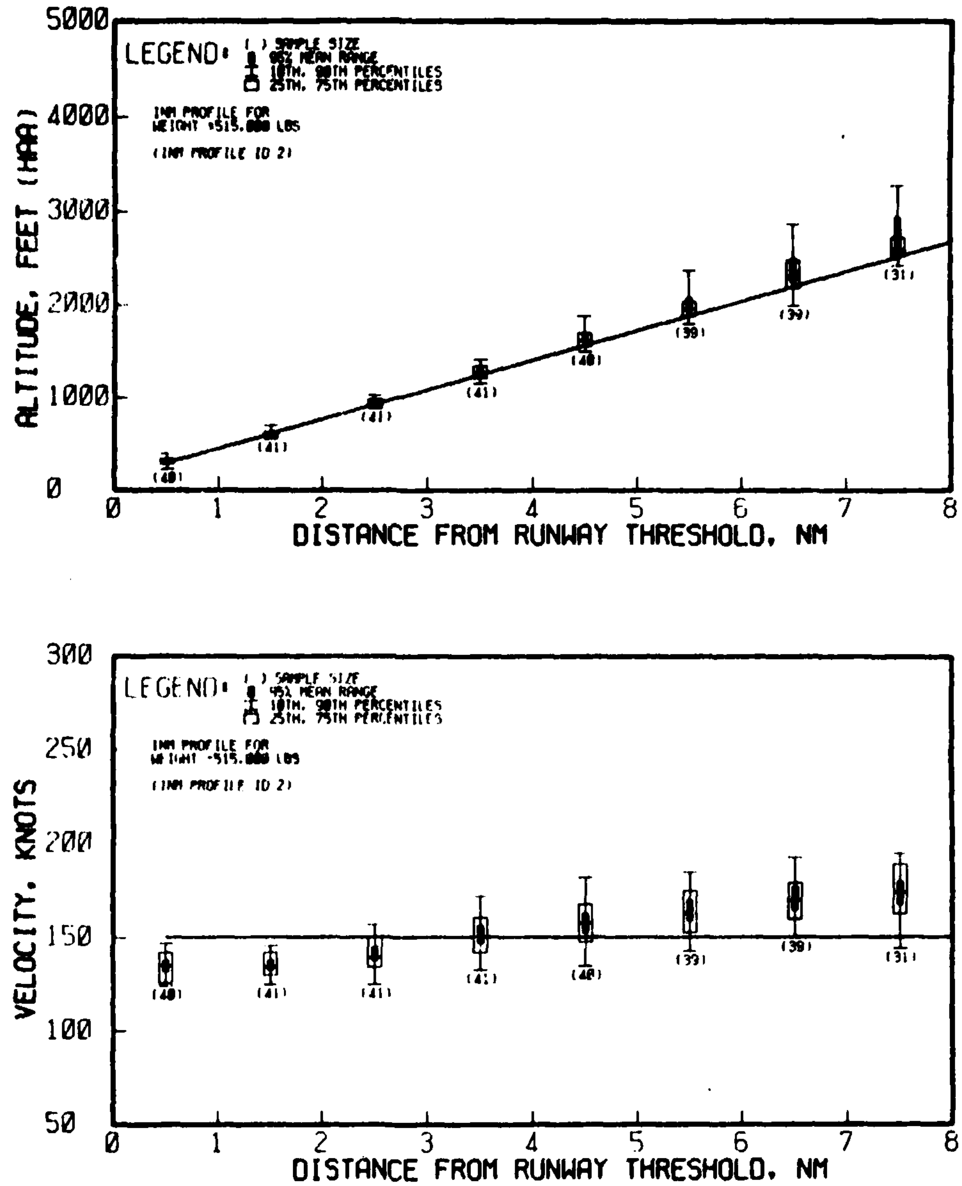



**FIGURE 3-7**
**OBSERVED AND INM PROFILES FOR B-747 ARRIVALS AT SEATTLE-TACOMA AIRPORT**

their speeds were much higher than the INM final approach speed. However, most of the six aircraft types slowed to within a few knots of the INM approach speed as they neared the runway. Under these decelerating approaches, the observed aircraft were usually established at near the INM speed before reaching a point 2 nautical miles from the end of the runway. The frequent occurrence of the decelerating approach in the Seattle data is consistent with the predominant conditions at Seattle: VFR weather conditions and fairly light traffic. These two factors enabled pilots to maintain a higher approach speed to a point closer to the runway.

The fairly close agreement between observed data and the INM for both altitude and velocity profiles close to the runway substantiates the accuracy of the data and the techniques used to process it. The presence of a VASI and/or an ILS glide slope gives all pilots more precise decent information and one would expect fairly close groupings of observed altitudes around the INM $3^{o}$ glide path. In addition, given the weather conditions and traffic loads of the Seattle-Tacoma Airport, one would expect pilots to employ a decelerating approach.

# 4. ANALYSIS OF DEPARTURES AND RESULTS

Unlike the fairly well-defined and standardized procedures for aircraft approaches and landings, there are many other factors associated with departures which contribute to considerably more variation in observed operations. Aside from procedural differences in takeoffs and departures, certain performance-limiting factors such as gross weight, pressure altitude, temperature, and runway surface conditions introduce additional sources of variation in observed departure profiles. A more detailed breakdown of departure operations was performed in order to assign specific causes to observed variations. This section describes an analysis of departure operations considered as a whole, and also describes two smaller analyses performed on subsets of the observed departures from Seattle.

In general, air carrier pilots are given more latitude in the execution of departures and can make tradeoffs between altitude, speed, and thrust. At a fixed thrust setting, for example, a pilot could elect to climb at a faster airspeed and sacrifice his rate of climb, or vice versa. In an attempt to standardize departure performance and enhance the safety and noise compatability of such operations, airline flight operations manuals specify well-defined departure procedures. However, pilot-to-pilot variability and the presence of extenuating circumstances such as turbulence or mountainous terrain near the airport suggest that less than strict adherence to procedures may be noted in observed profiles.

## 4.1 Common Operating Practices for Departures

A review of several flight operations manuals revealed that most airlines employ departure procedures which are in basic compliance with the suggested FAA procedures contained in AC91-53. This advisory circular has been in effect since October 1978, and outlines a suggested noise abatement procedure for turbine powered aircraft departures. There are differences between the procedures of various airlines, however, which could result in tangible differences in the resulting profiles.

The FAA departure procedure is designed to reduce the noise generated by the turbine engine itself through reductions in thrust and to increase the distance between the source (the airplane) and the noise affected area on the ground by increasing climb gradient. The departure is also intended to be consistent with the objectives of safety and fuel efficiency.

A diagram of the FAA departure is given in Figure 4-1. Speed, thrust, and flap changes are scheduled according to gains in altitude. After lift-off, all aircraft climb at a speed of $V_2$ plus 10 to 20 knots at takeoff thrust. The symbol $V_2$ represents "takeoff safety speed" and it varies with aircraft weight and flap setting for each aircraft type. It is the speed at which, should one engine fail, the airplane is still capable of maintaining a specified minimum climb gradient. When the airplane reaches a height of 1000 feet above the airport, flaps are retracted according to the schedule in the flight operations manual and an acceleration is made to $V_{zf}$, the minimum zero flap maneuvering speed. At this point, thrust is reduced from takeoff power. The difference between the FAA and some airline procedures is the size of the thrust "cutback".

Under the procedures of some airlines, a reduction is made to the normal climb thrust for all aircraft types. The FAA procedure, however, specifies a cutback which is based on the type of engines involved. Airplanes with high bypass ratio engines reduce to normal climb thrust while those with low bypass ratio engines reduce to a value somewhat below normal climb thrust. The lower thrust must still be capable of providing a prespecified minimum climb gradient in the event an engine fails. Aircraft with the quieter high bypass ratio engines are predominantly two, three, and four engine wide-bodied aircraft while most of the narrow bodied fleet are powered by low bypass ratio engines. Regardless of which power setting is used, both the FAA and the other procedures recommend the climb be continued at or near $V_{zf}$ until reaching 3000 feet. At that altitude all aircraft accelerate to 250 knots and resume a normal en route climb configuration.

Of the several airlines conducting operations at Seattle, some have adopted the FAA departure while others have used their own type of departure. The FAA and other departures for wide bodied aircraft with high bypass ratio engines are essentially the same and one would expect similar performance profiles if all other factors are equal. On the other hand, the difference between the FAA and other departures for aircraft with low bypass ratio engines is the thrust cutback at 1000 feet altitude. Under the FAA procedure, one would expect a shallower climb profile above 1000 feet than the one obtained using other procedures. Other factors may obscure the differences attributable to the use of varying procedures, however. Almost all flight operations manuals, in addition, include a caveat stating that the noise abatement profiles may be abandoned, including the thrust reduction at 1000 feet, to meet turbulence, air traffic, or obstacle clearance requirements.

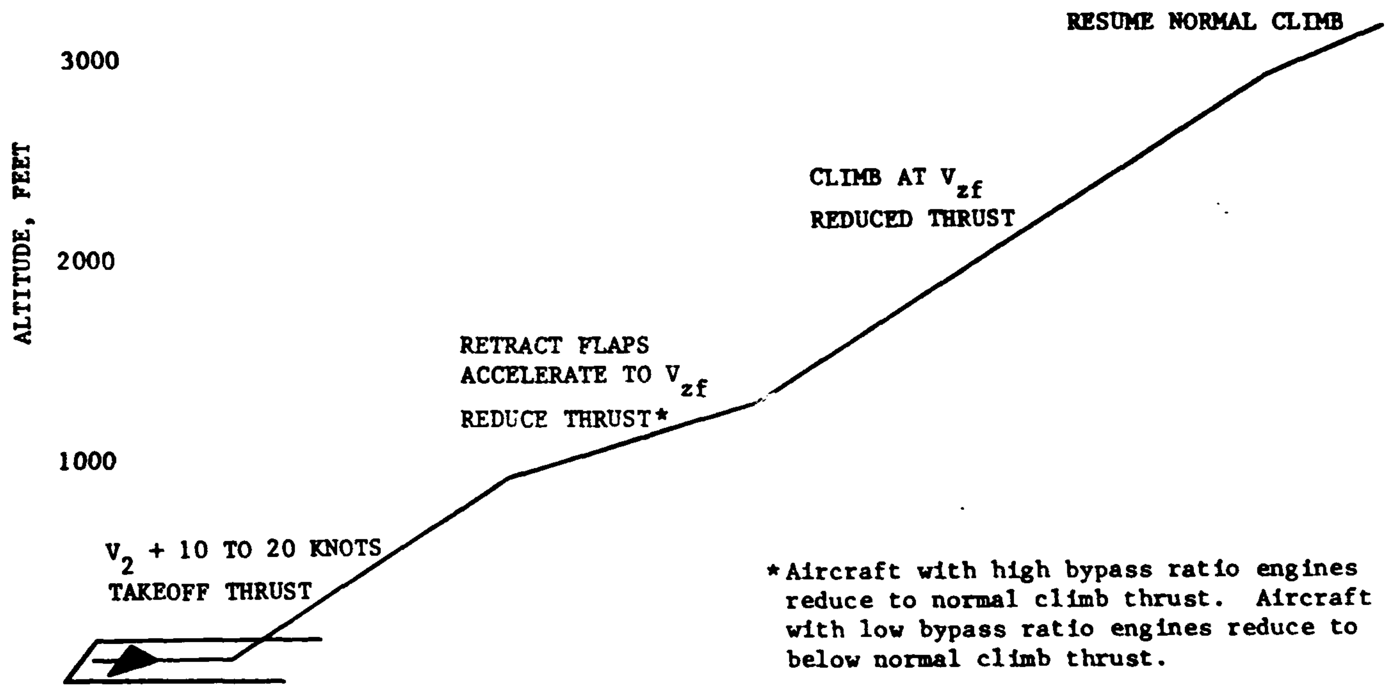



**FIGURE 4-1**
**FAA NOISE ABATEMENT DEPARTURE PROFILE**

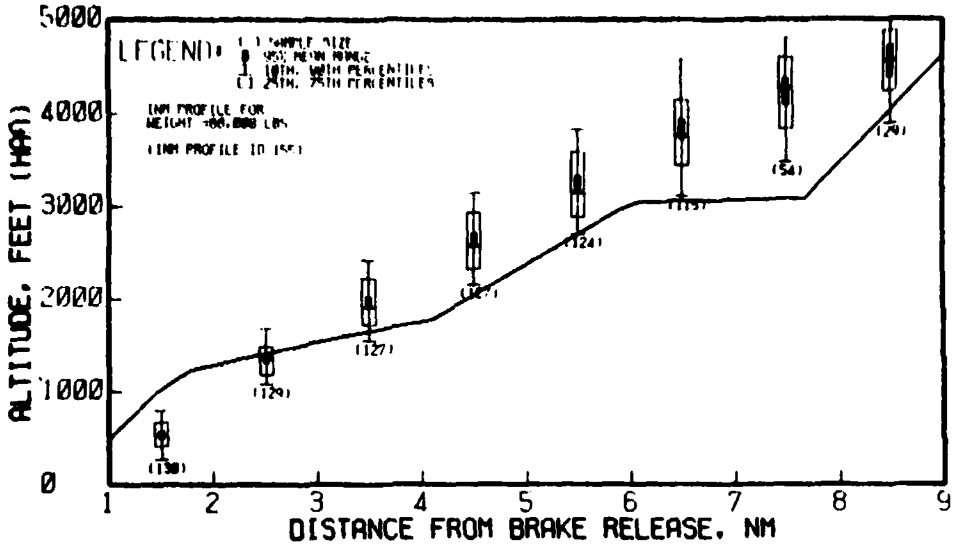
## 4.2 INM Departure Profiles

The departure profiles contained in the INM data base are completely defined profiles and have been constructed from theoretical relationships based on engineering data. In constructing the profiles, all aircraft were assumed to follow the FAA departure as described in AC91-53. To control the effect of varying aircraft departure weights, the INM has up to seven slightly different profiles to reflect departure performance of each aircraft type at different weights. The user of the INM supplies information on the weight of each proposed departure indirectly by specifying the stage-length (the non-stop distance) of the flight. The INM bases its estimation of weight on stage-length under the assumption that weight and stage-length are proportional. This appears to be a reasonable assumption since, as the length of a flight increases, the fuel load must also increase. There are cases, however, where this assumption is not true. An aircraft making a series of short flights, for example, may depart on the first leg with enough fuel for all the legs of the flight to eliminate the need to refuel at each stop. Airlines will sometimes refuel only at certain airports where the price of fuel is lower and carry enough fuel to fly through other airports where prices may be higher.

For the purposes of comparing INM profiles with observed profiles, the INM profile for the most likely stage-length was chosen for each aircraft type. The determination of the most likely stage-length was based primarily on the type of aircraft. Some aircraft are intended for short-haul flights and others are designed for long range flights. For those aircraft types which fly a wide range of stage-lengths the actual stage-length was determined for specific flights by consulting airline schedules, and the most frequently occurring stage-length was selected as the representative stage-length.

## 4.3 Results of INM - Observed Departure Profile Comparison

Figures 4-2 to 4-7 on the next pages show the comparisons of observed profile data to INM profiles for the same six types of aircraft. Like the comparisons made for arrivals, the INM profile for the most likely aircraft model and stage-length is presented in the form of a solid line for each aircraft type. Observed profile data are again characterized by box-and-whisker plots. Unlike the case for arrivals, however, no uniform trends are apparent when the comparisons are made. To facilitate the



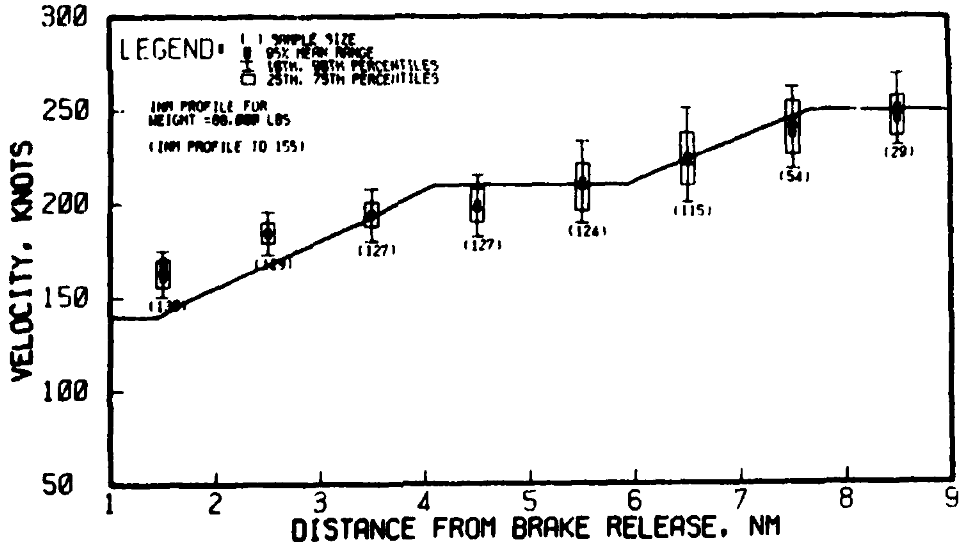
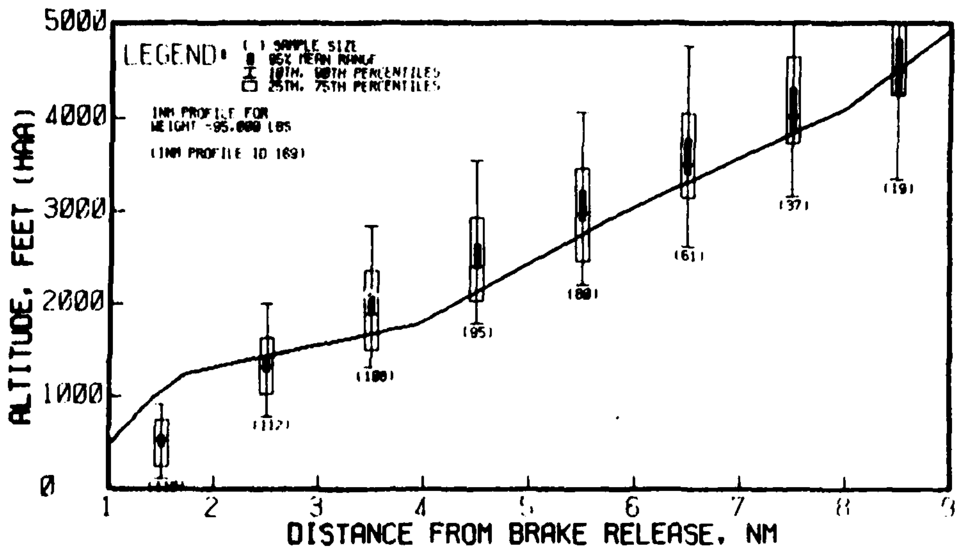




**FIGURE 4-2**
**OBSERVED AND INM PROFILES FOR DC-9 DEPARTURES FROM SEATTLE-TACOMA AIRPORT**



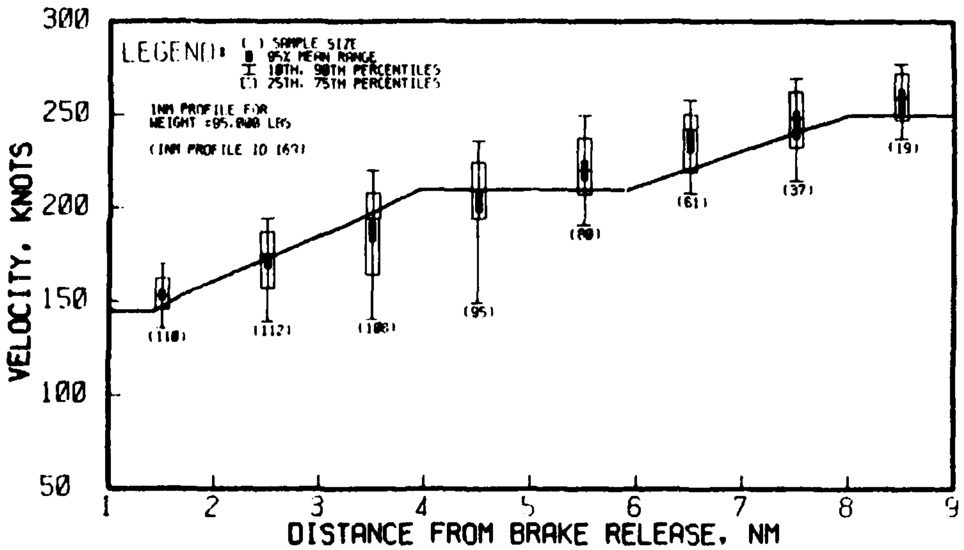




**FIGURE 4-3**
**OBSERVED AND INM PROFILES FOR B-737 DEPARTURES FROM SEATTLE-TACOMA AIRPORT**

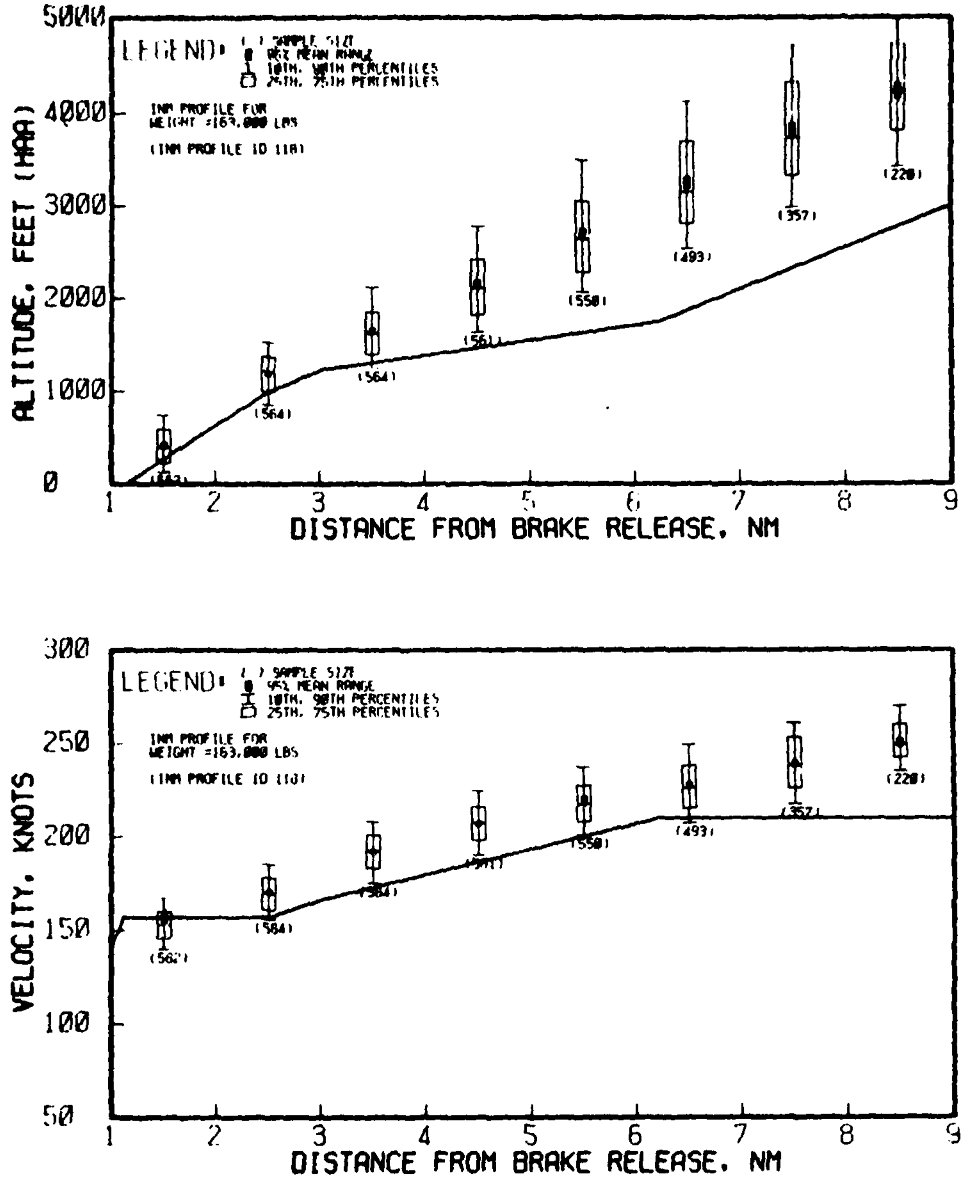
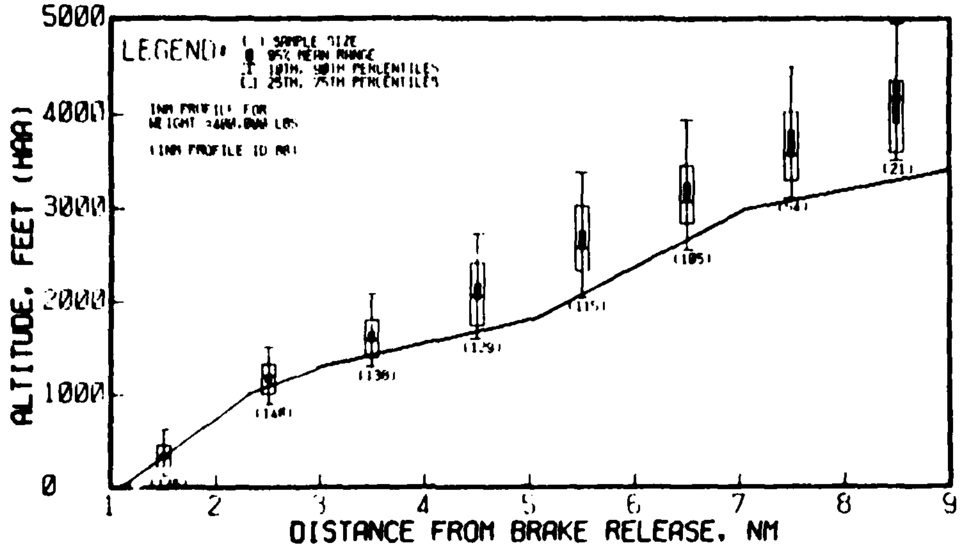



**FIGURE 4-4**
**OBSERVED AND INM PROFILES FOR B-727**
**DEPARTURES FROM SEATTLE-TACOMA AIRPORT**



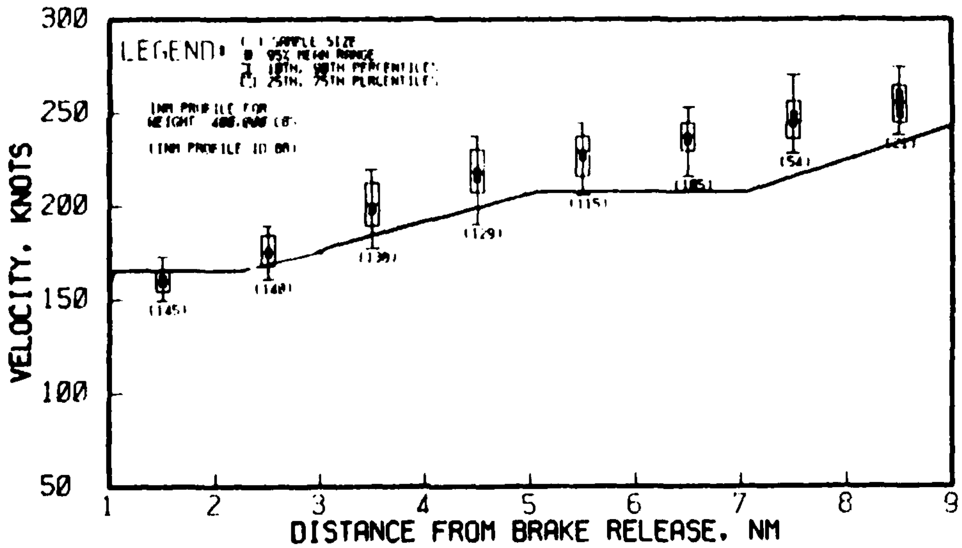




**FIGURE 4-5**
**OBSERVED AND INM PROFILES FOR DC-10 DEPARTURES FROM SEATTLE-TACOMA AIRPORT**

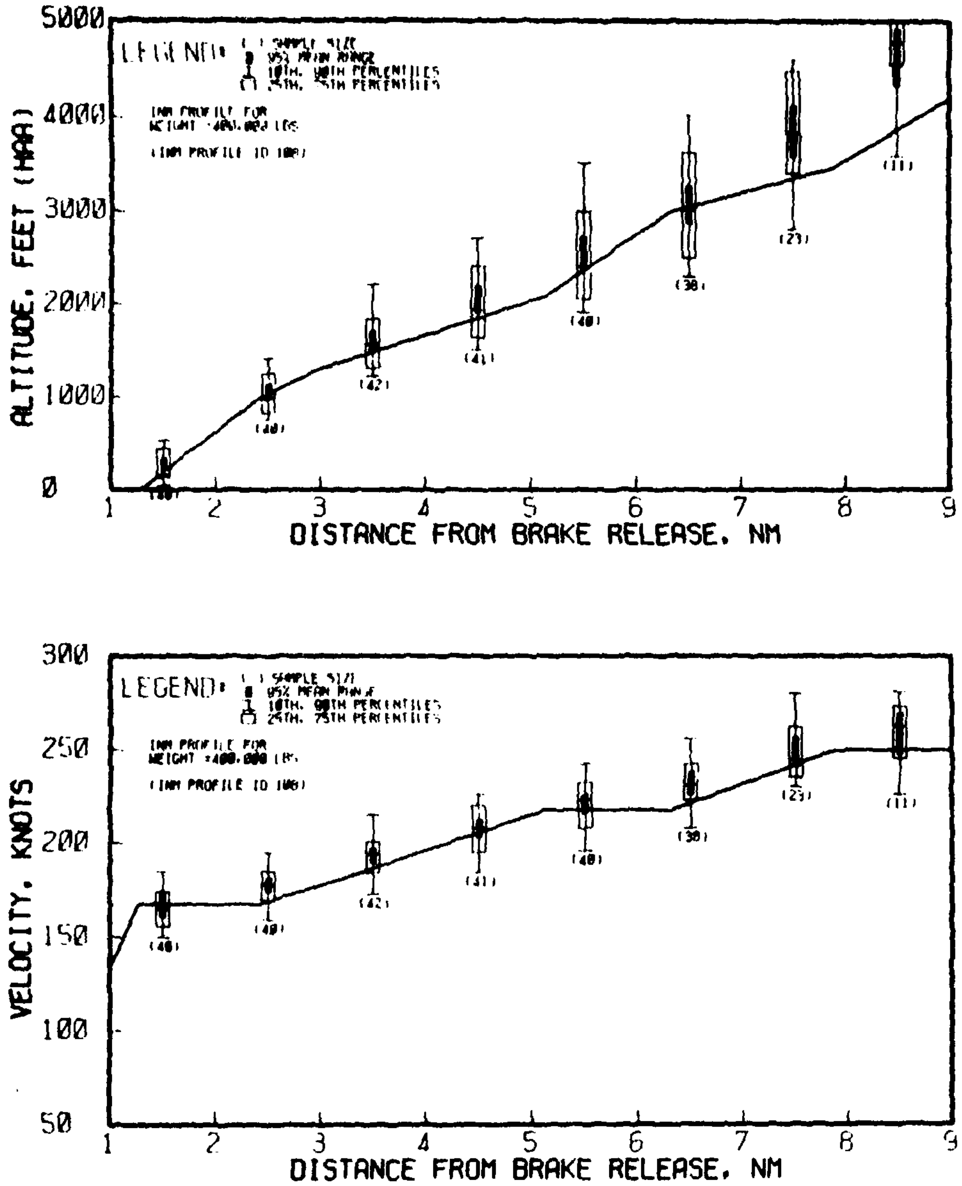



**FIGURE 4-6**
**OBSERVED AND INM PROFILES FOR L-1011 DEPARTURES FROM SEATTLE-TACOMA AIRPORT**

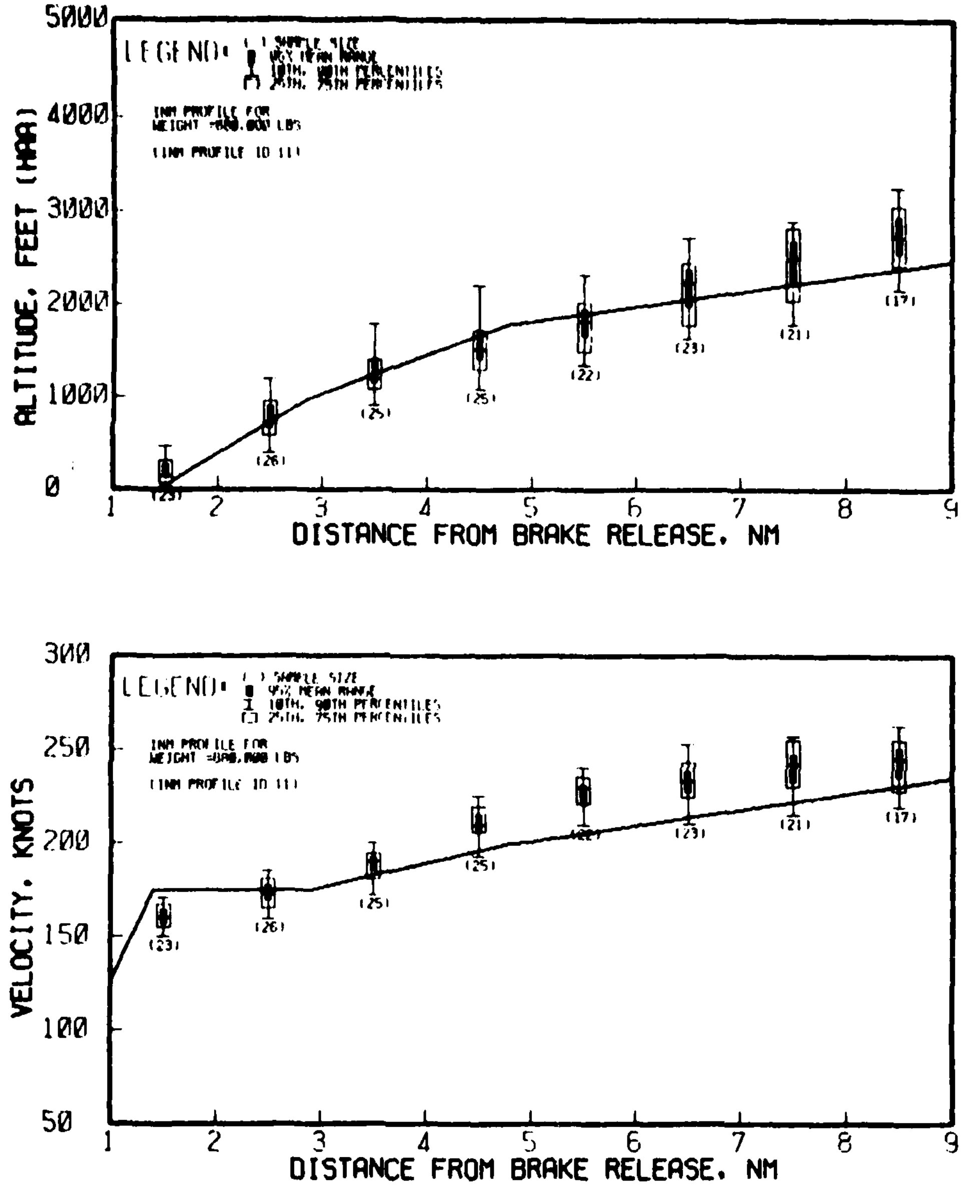



**FIGURE 4-7**
**OBSERVED AND INM PROFILES FOR B-747**
**DEPARTURES FROM SEATTLE-TACOMA AIRPORT**

discussion of the level of agreement between INM and observed profiles, the departure profile is divided into two segments: the near field segment (which includes the portion of the departure within 3 nautical miles from the BRP) and the far field segment (which includes the portion more than 3 nautical miles from the BRP).

A visual inspection of the altitude profiles for observed departures and the INM for the near field shows that the two were in fairly close agreement for the B-727, DC-10, L-1011, and B-747. For the two twin-engine, narrow bodied aircraft, however, the DC-9 and B-737, the observed altitudes for the near field were much lower than specified by the INM. The difference in altitude was approximately 500 feet for these aircraft. The near field velocity profiles for observed operations were within reasonable agreement with INM velocities for all six aircraft types. A closer inspection of the near field INM profiles for the DC-9 and B-737 reveals that the INM predicts an altitude gain of 500 feet by the time the aircraft has traveled one mile from the BRP. Although such performance is attainable under optimum conditions, it is probably not representative for these two types of aircraft.

For the far field segment, the observed altitude profiles for the DC-9 and B-727 were much higher than specified by the INM. The altitude difference was in the range of 500 to 1500 feet. For the four other aircraft types, observed altitudes were fairly close to INM altitudes. The observed velocity profiles for the far field were in close agreement with INM velocities for all aircraft except the B-727. For this aircraft observed velocities were 20 to 50 knots higher than INM velocities.

One reason for the differing levels of agreement is the difference in the thrust reduction specifications of the departure profiles. As mentioned earlier, the FAA and other types of departures are essentially the same for aircraft with high bypass ratio engines such as the DC-10, L-1011 or B-747. Because the INM profiles reflect theoretical performance using the FAA departure procedures, and because most airlines use either the FAA or similar procedure as the standard departure, one would expect fairly close agreement between the observed operation and INM profiles for wide-bodied aircraft. This expected close agreement is evident in Figures 4-5 through 4-7.

The FAA and some departure procedures for low bypass ratio engines, on the other hand, are somewhat different. The expected result of the difference is for those airlines not using the FAA procedure to have a steeper climb gradient for the segment between 1000 feet and 3000 feet above field elevation. The low bypass engine aircraft in this study, the DC-9, B-727, and B-737 were all observed to be higher for this phase of the departure than the INM profile, as evident in Figures 4-2 through 4-4.

### 4.3.1 Analysis of B-727 Departures Grouped According to Airline

An analysis was made of Boeing 727 departures to determine if differences in departure procedures in the flight operations manuals of different airlines have observable effects on actual operations. B-727 operations made up, by far, the majority of operations at Seattle. It was possible, therefore, to group B-727 departures according to airline and still have reasonably large sample sizes. Five major airlines were considered in this analysis.

Rather than making comparisons with INM profiles, the observed departure profiles for each airline are compared directly with other airlines in Figure 4-8. The dashed lines in this figure connect median values over each sampling station for each airline.

By referring to the altitude profiles in Figure 4-8, it is evident that there is no real difference in climb performance between the different airlines for the departure segment within 5 nautical miles of the BRP. Beyond this point, however, one finds the disparity becoming more distinct. At 8.5 nautical miles from BRP the highest median departure is approximately 1000 feet higher than the lowest median departure. A review of available flight operations material indicates that this is an expected result. The airline with the lowest median departure uses a procedure which represents a unique approach to noise abatement and was constructed in the manner ultimately intended by FAA AC91-53. This airline reduces to a significantly lower thrust value at 1000 feet altitude than specified by manuals of other airlines. The expected result of this cutback is the shallower climb angle evident in the median of these departures.

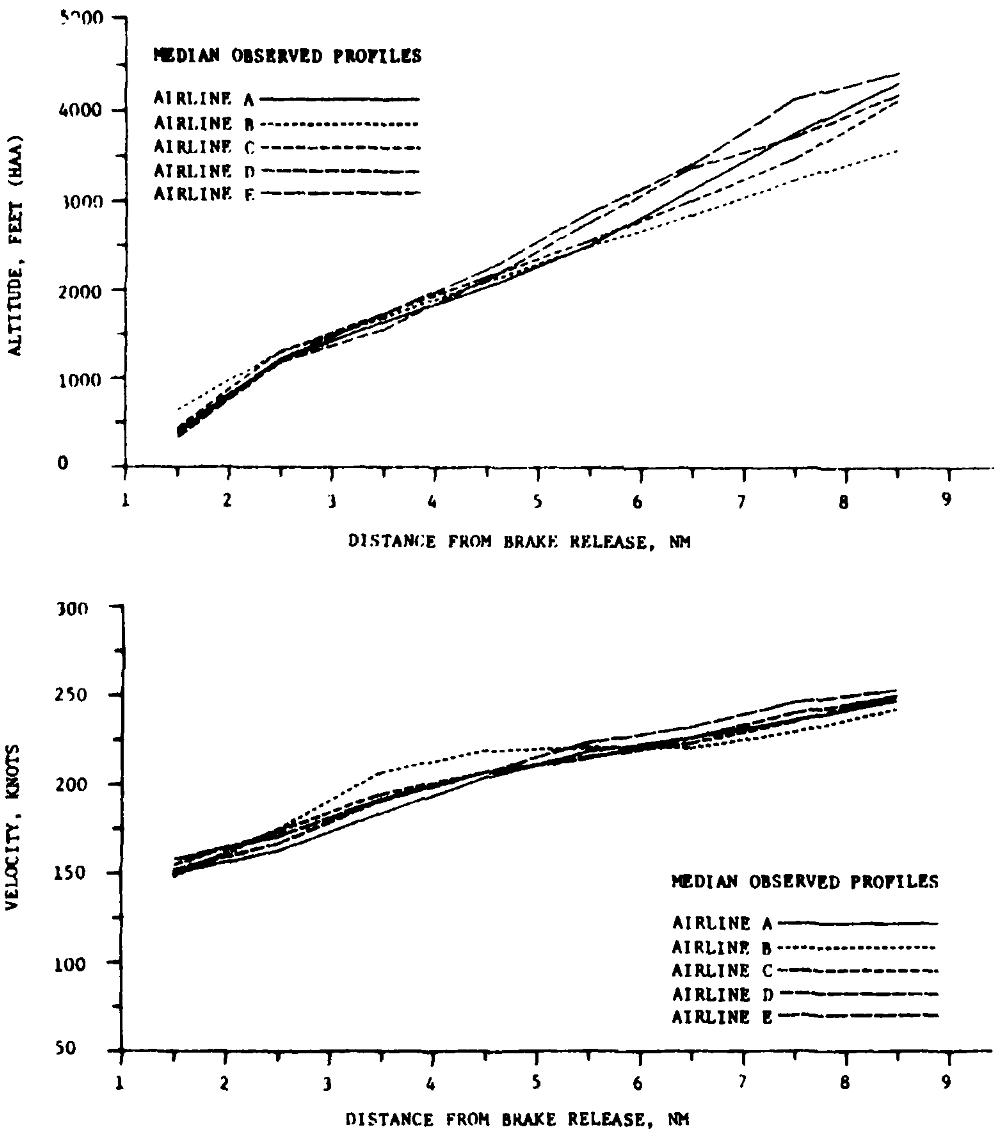



**FIGURE 4-8**
**OBSERVED PROFILES FOR B-727 DEPARTURES GROUPED ACCORDING TO AIRLINE**

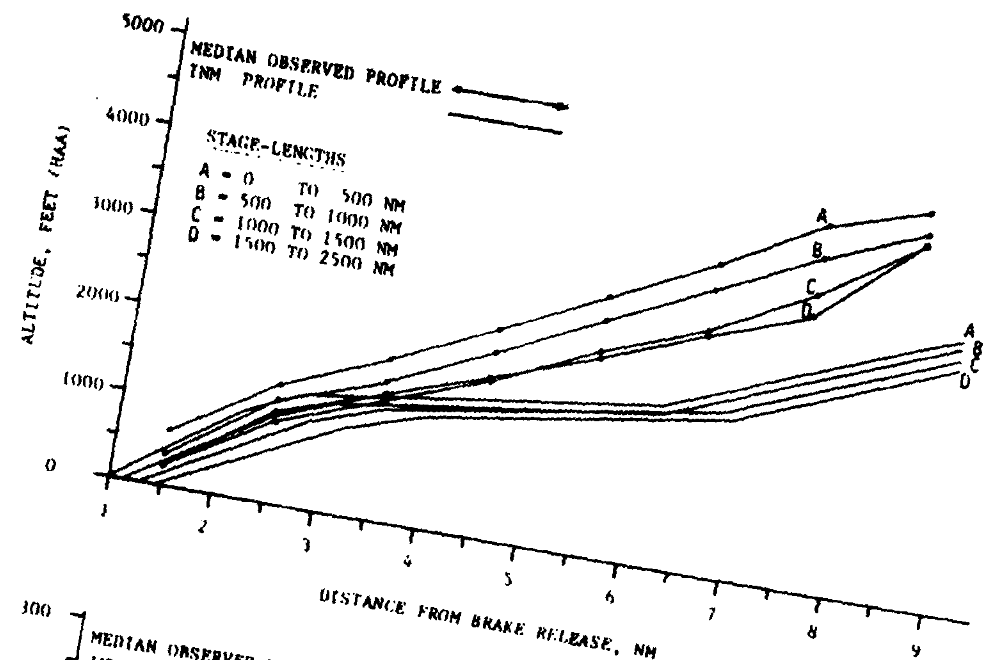
Reference to the velocity profiles in Figure 4-8 on the other hand, reveals no significant differences in the airspeed schedules used by the five airlines studied. This is also an expected result since the departures of most all airlines use the same target speeds. The similarity of the velocity profiles provide additional support to the hypothesis that differences in thrust cutbacks provides the largest single source of variation in the altitude profiles in Figure 4-8.

### 4.3.2 Analysis of B-727 Departures Grouped According to Stage-Length

As mentioned earlier, the INM estimated the weight of each departing aircraft on the basis of the stage-length for the flight. To measure the sensitivity of both observed operations and INM profiles to differences in stage-length, a separate analysis was conducted on B-727 departures grouped according to stage-length. The actual stage-length of each flight was determined by reference to the flight intinerary in airline schedules. Each B-727 departure for which the first point of intended landing could be determined was assigned to one of four stage-length categories: 0 to 500 nautical miles, 501 to 1000 miles, 1001 to 1500 miles, and 1501 to 2500 miles. The same statistical analyses were performed on B-727 grouped as such and the results were compared with the INM B-727 profiles for the corresponding stage length. The same conclusions apply to B-727 departures grouped according to stage-length as for B-727 departures considered as a whole in Figure 4-4. For all four stage-lengths observed altitudes were close to the INM profiles for the near field segment, but for the far field segment the differences approached 1500 feet. Observed velocities in each case were slightly higher than corresponding INM profiles.

A direct comparison of the INM profiles for the four stage-lengths is given in Figure 4-9. The median profiles for observed operations are also given. The INM altitude and velocity profiles in this figure indicate that there is little difference between the shortest stage-length and the longest stage-length. The median altitude profiles for observed operations indicate only a slightly greater sensitivity to differences in stage-length than the corresponding INM altitude profiles.

An important observation to make at this point concerns the sensitivity of INM profiles to stage-length differences in Figure 4-9 and the fairly wide variation in observed



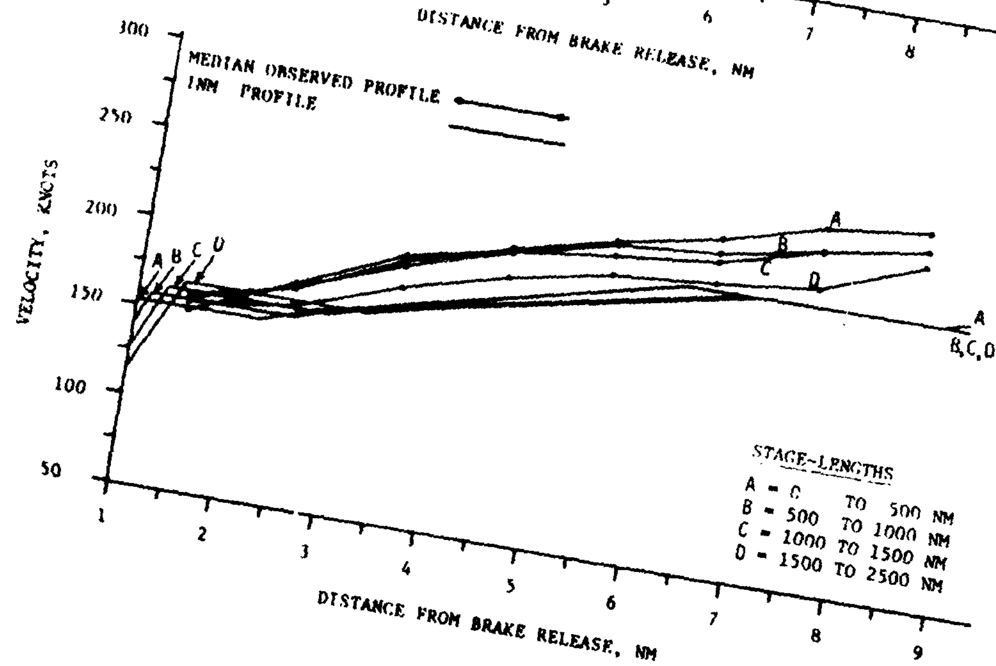
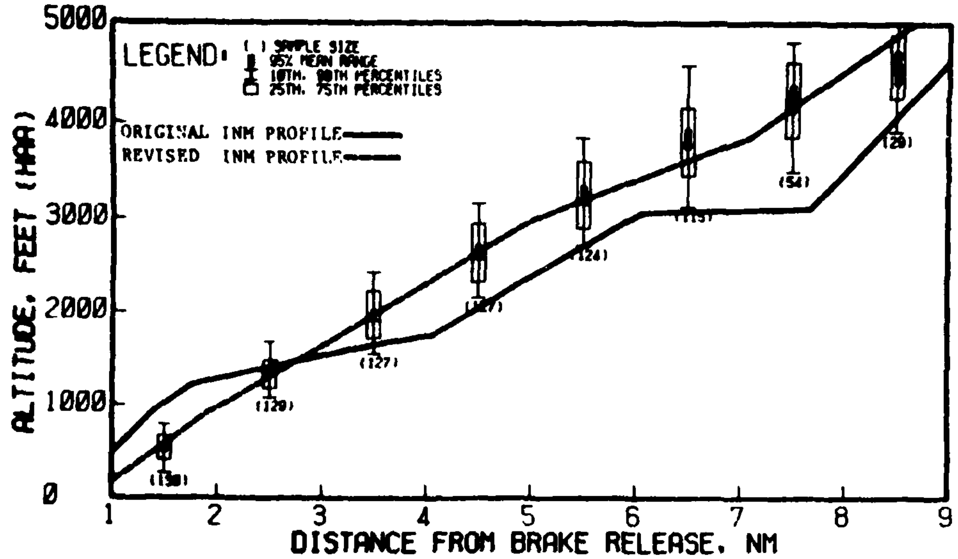




**FIGURE 4-9**
**INM AND OBSERVED PROFILES FOR B-727 DEPARTURES GROUPED ACCORDING TO STAGE-LENGTH**

operations (as evidenced by the wide spacing of the 10th and 90th percentiles in the box-and-whisker plots in Figures 4-2 through 4-7). The variation in observed operations is several times greater than the sensitivity of the INM to changes in stage-length. The result of such a situation is for the slight effects of stage-length to be obscured by variations caused by other factors. It is not necessary, then, to maintain such precise differences in INM profiles for the stage-length factor if such differences are small compared to real world variation from other sources. Fewer and more broadly defined stage-length categories may be more efficient.

#### 4.3.3 Comparison of Observed Departure Profiles for DC-9, B-737, and B-727 with Revised INM Profiles

The original Number 8 INM departure profiles were constructed under the assumption that, for all aircraft types, airlines employed the FAA noise abatement departure profile as outlined in AC91-53. However, the observed data for the low bypass ratio engined aircraft in the study (DC-9, B-737, B-727) suggested that for these three types of aircraft, this may not be the case. In an effort to improve the level of agreement between Version 8 INM profiles and observed data, the FAA Office of Energy and Environment proposed a few revisions to the INM profile data base for these three aircraft types. The revised profiles were not merely molded to fit the observed data but rather were constructed using the same theoretical relationships under different assumptions about the departure procedures used. As shown in Figures 4-10 through 4-12, which show the original and revised INM profiles and the observed profile data, the level of agreement is considerably improved with the revised INM profiles.



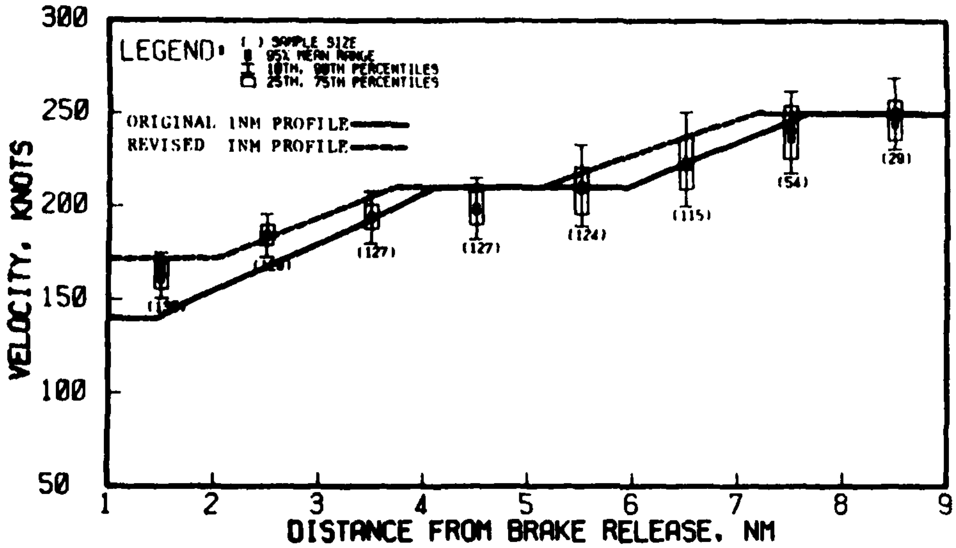
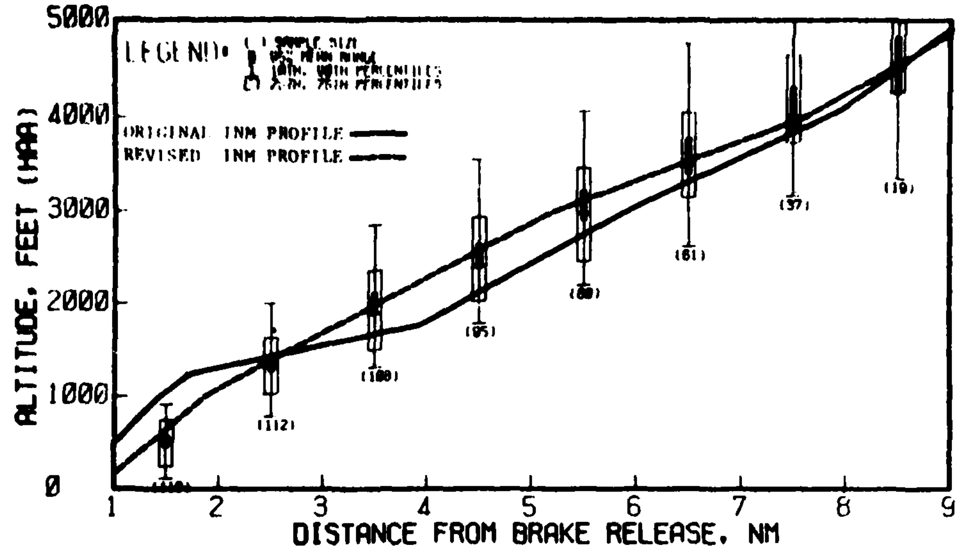




**FIGURE 4-10**
**ORIGINAL AND REVISED INM PROFILES FOR DC-9**



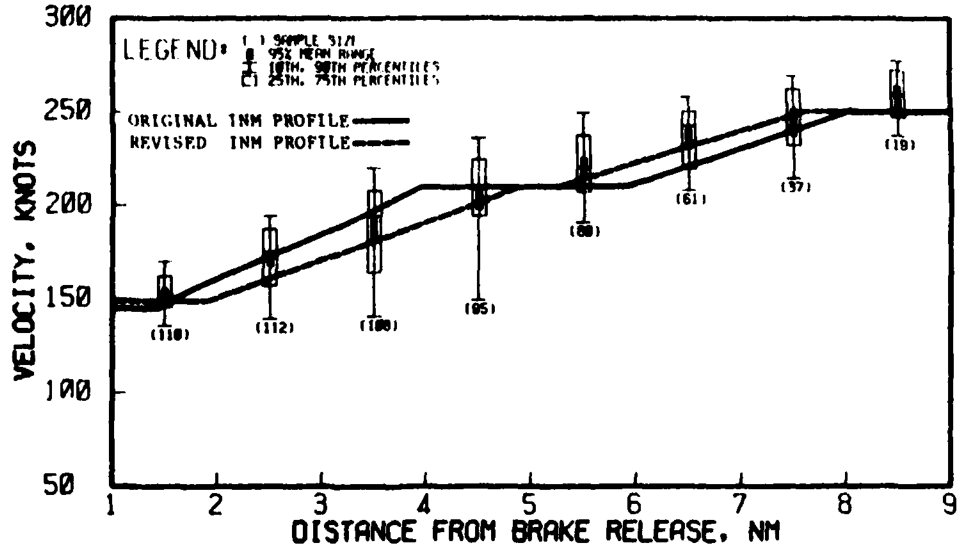




**FIGURE 4-11**
**ORIGINAL AND REVISED INM PROFILES FOR B-737**

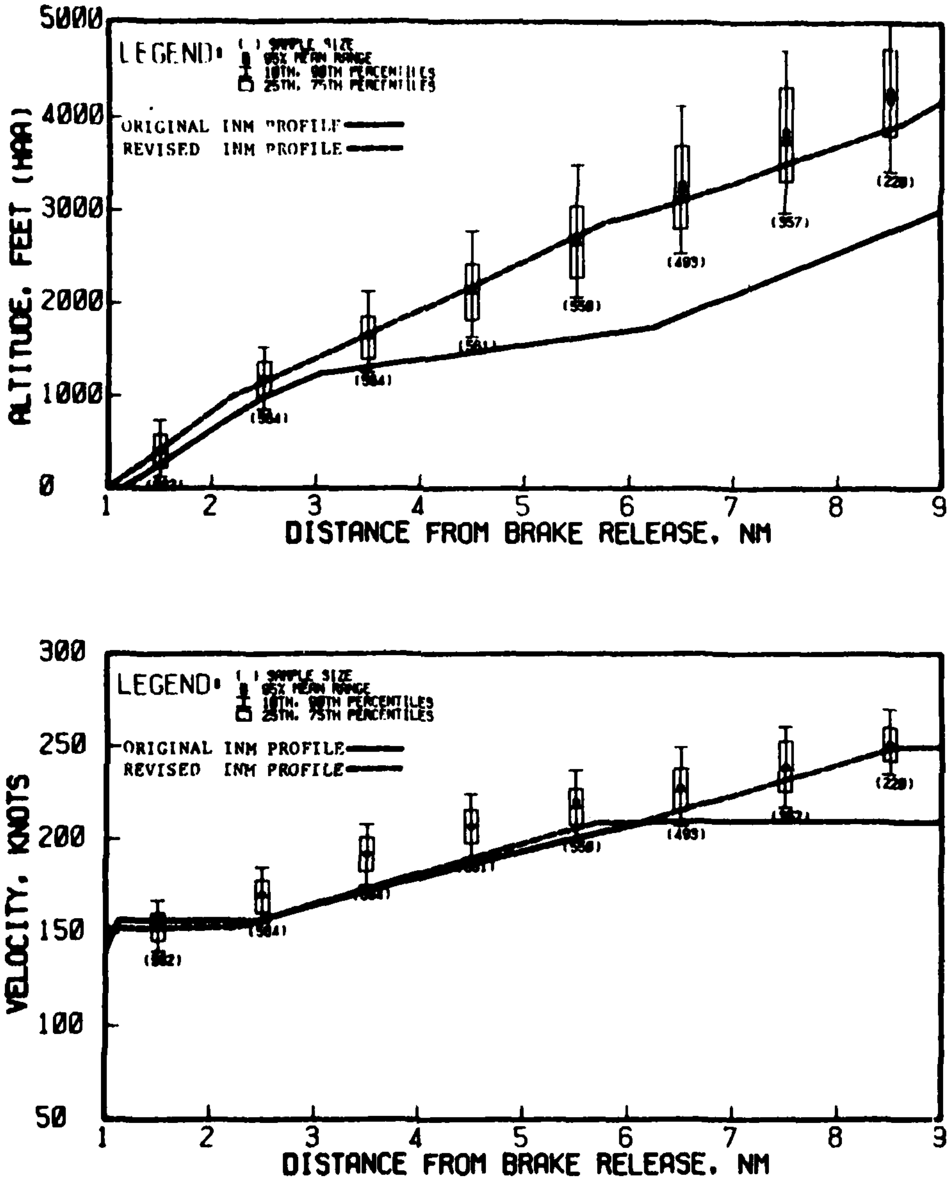



**FIGURE 4-12**
**ORIGINAL AND REVISED INM PROFILES FOR B-727**

## 5. CONCLUSIONS AND RECOMMENDATIONS

This analysis of aircraft profiles represents the most comprehensive comparison made to date between observed operations and profiles contained in the INM data base. A more complete review of airline operating practices has been included to reveal those operational variables which are likely to influence the shape of observed profiles. In general, the new Number 8 INM data base profiles have made significant improvements in observed-INM profile agreement. There are, however, a few areas where the agreement could be improved even further and INM ease-of-use and efficiency enhanced.

For arrivals, the agreement between observed operations and standard INM approach profiles was generally good. The standard INM altitude profile depicts a continuous descent on a $3^{o}$ glide slope to the point of touchdown. Observed arrivals for all six types of aircraft were closely grouped around this glide slope. A difference was noted, however, in the comparison of observed and INM velocity profiles for arrivals. Standard INM velocity profiles depict an approach of constant speed for the last 9 nautical miles before the threshold. Observed aircraft, however, approached the airport area at a significantly higher speed and gradually reduced speed to the final approach speed approximately 2 nautical miles from the runway threshold. This observation was attributed to the prevalence of weather and traffic conditions which made decelerating approaches feasible.

Though the INM user could construct his own decelerating approach to accommodate such a situation, the predictable patterns of observed operations suggest that the addition of a completely predefined decelerating approach would be more efficient, consistent, and of greater benefit to the user. The user would have to be informed of the weather and traffic conditions which make either the constant speed or decelerating approach applicable, but the benefit gained in establishing this choice is the simplicity in which the user can specify entire approach profiles which are based on predictable and fairly invariant observed operations.

Another issue concerning decelerating approaches is the effect they have on estimated and observed noise levels. The thrust values contained in the INM approach profile data base are specified for aircraft maintaining a given configuration in a

"steady state". An aircraft which is decelerating, however, is not in a steady state and is probably using less thrust than an aircraft maintaining a constant speed in the same configuration. The end result of the decelerating approach should be some reduction in noise generated at the source. However, the size of the noise reduction may be small because thrust levels are generally low even in constant speed approaches.

For departures, the comparisons made between INM profiles and observed operations showed little difference for some aircraft types and greater differences for others. In general, observed-INM profile agreement was better for wide-bodied aircraft with high bypass ratio engines. The close agreement was attributed to the similarity between assumptions under which the INM profiles were constructed and actual operating practices used by various airlines.

The observed-INM agreement was not quite as good for narrow-bodied, low bypass ratio engined aircraft. For the near-field segment of the departures, INM profiles for the B-737 and the DC-9 were much higher than observed operations. The INM profiles for these two aircraft for this segment reflect rather steep climbs which are probably not attainable in everyday operations. On the far field, differences were noted for the DC-9 and B-727. The observed trends suggest that the thrust cutbacks in actual operations are not as great as those assumed by the INM profiles. Some airlines employ a departure which specifies a smaller thrust reduction than the FAA departure for low bypass ratio engines.

The analyses of B-727 departures grouped in various ways also contributed to a greater understanding of the pertinent variables involved in departures. An analysis of B-727 departures grouped according to airline revealed that some differences in observed profiles could be traced to differences in operating procedures. Another analysis performed on B-727 departures grouped according to stage-length resulted in the same conclusions as when they were considered in aggregate. Differences between INM profiles for the shortest and longest stage-lengths are not great and tend to be masked over by variation from other sources. In addition, the assumption that weight estimation can be based on stage-length may not be true for all instances. Based on these findings the number of stage-length categories should be reduced from seven to two or three.

The revisions to the INM profiles proposed by the FAA for the DC-9, B-737, and B-727 aircraft resulted in much improved observed-INM profile agreement. The revised profiles were the

result of recomputing departure performance under different assumptions about the departure procedures being used. To guarantee that the INM profiles maintain relevance with general observed operations, the revised profiles should become a permanent part of the INM data base.

In conclusion, the INM profiles contained in the new Number 8 data base generally agree with current observed profiles. The level of agreement is much better than afforded by the older Number 7 data base. However, the improvements suggested above would lead to even closer agreement and ease the tasks presented to the INM user.

# APPENDIX A

## ANALYTICAL TECHNIQUES USED TO PROCESS RADAR DATA

ATC Radar Beacon System (ATCRBS) target data as reported to the ARTS-III system were used to determine the altitudes and velocities of aircraft as they passed over the sampling stations on an arrival or departure. It was necessary to smooth the data before it could be used to yield altitude, position, and velocity information. This Appendix describes the cubic spline function smoothing technique, used to account for the above mentioned problems, and the other analytical techniques used to determine altitude and velocity at the closest point of approach.

An ARTS-III target report describes an aircraft's position in terms of the Mode C altitude reported by the aircraft's transponder, azimuth angle (relative to Magnetic North), and range from the ATCRBS antenna. The range value is quantized to the nearest one-sixteenth of a nautical mile and the altitude to the nearest 100 feet. The ARTS-III system automatically corrects the reported altitude for non-standard pressure and yields the aircraft's altitude relative to Mean Sea Level (MSL). The MITRE ARTS81 data extraction program translates each pertinent target report to a position report in terms of a 3-axis Cartesian coordinate system.

A radar track history of an aircraft arrival or departure consists of a chronologically ordered *series of position reports*, $\{p\}$. The ith position report in the series can be written parametrically as

$$P_i = (x_i, y_i, z_i, t_i)$$

where

$x_i$ = aircraft displacement from the extended runway centerline, in feet,

$y_i$ = aircraft displacement along the extended runway centerline from a fixed arbitrary point on the runway, in feet,

$z_i$ = altitude of aircraft, in hundreds of feet above the runway,

$t_i$ = the time at which the position report occurred, in seconds.

The time interval between successive position reports, $(t_i - t_{i-1})$, was approximately 4.7 seconds.

An estimate of the time of closest point of approach, CPA, to each sampling station was based on the raw position data. For sampling station j, with a location $y_j{}^*$, a consecutive pair of position reports $(p_i, p_{i+1})$ was found such that

$$y_i \geq y_j{}^* \geq y_{i+1}$$

The time of the closest point of approach, $t_j{}^*$ was then estimated using linear interpolation.

The four reports preceeding and following the time of CPA were then used in a smoothing operation called cubic spline function smoothing. The desired product of the smoothing process was a set of 3 cubic equations, x(t), y(t), and z(t), which provides a continuous description of aircraft position along the appropriate dimensions with time as the independent variable. The three equations describing aircraft position have the form

$$x(t) = A_x + B_x t + C_x t^2 + D_x t^3,$$

$$y(t) = A_y + B_y t + C_y t^2 + D_y t^3,$$

$$z(t) = A_z + B_z t + C_z t^2 + D_z t^3.$$

The coefficients A, B, C, and D, were determined using polynomial interpolation. In performing the interpolation, however, the smoothing process is introduced by having the objective that the acceleration on any axis (e.g., $\ddot{x}(t)$, $\ddot{y}(t)$, and $\ddot{z}(t)$) be minimized. This objective is applicable to the treatment of the equations of motion for transport category aircraft because the accelerations (changes in velocity or direction) in such aircraft operations are relatively slow. To meet this objective, the "strict" polynomial interpolation technique, where the equations must pass exactly through the data points, is relaxed so that candidate curves need only come within a specified range of the data points. This acceptable range is proportional to the magnitude of the error expected in the raw data. The errors associated with the input data are such that tolerable ranges through which the curves must pass permit considerable smoothing without oversmoothing the data to a straight line. A full discussion of the cubic spline smoothing technique is presented in Reference 3.

Once the three smoothed equations of motion were known, the altitude and velocity of the aircraft at the time of CPA was determined. The altitude at the time of CPA was determined by the evaluation of

$$z(t_j{}^*) = A_z + B_z t_j{}^* + C_z (t_j{}^*)^2 + D_z (t_j{}^*)^3.$$

The velocity was determined by first taking the first derivatives of x(t) and y(t). The velocity was then determined along each dimension using the resulting velocity equation, $\dot{x}(t)$ and $\dot{y}(t)$,

$$\dot{x}(t_j^*) = B_x + C_x t_j^* + D_x (t_j^*)^2$$

$$\dot{y}(t_j^*) = B_y + C_y t_j^* + D_y (t_j^*)^2$$

The absolute velocity estimate was then determined by

$$V^* = \sqrt{\dot{x}^2 + \dot{y}^2} \qquad \text{at } t_j^*$$

As an example of the desirability of cubic spline function smoothing in the treatment of ARTS data, Figure A-1 shows the averaged velocity profile and the smoothed velocity profile of an actual departure from the Seattle-Tacoma airport. The averaged velocity profile was determined from untreated ARTS-III position data by the following relation on a report-to-report basis.

$$AVG = \frac{\Delta d}{\Delta t}$$

where $\Delta d$ = distance traveled
$\Delta t$ = the time interval (usually 4.7 seconds).

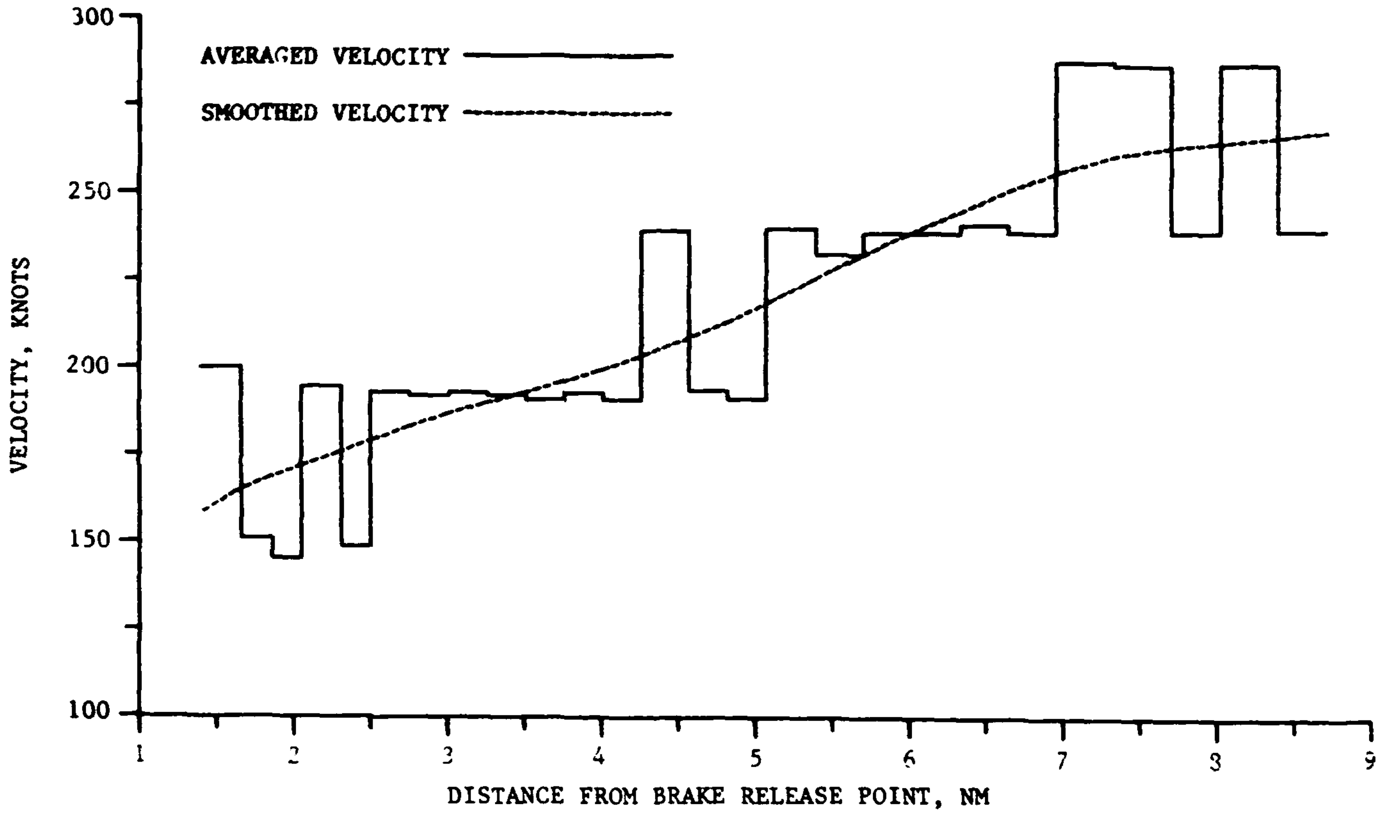



**FIGURE A-1**
**COMPARISON OF AVERAGED AND SMOOTHED VELOCITY FOR AN ACTUAL DEPARTURE FROM SEATTLE-TACOMA AIRPORT**

## APPENDIX B

## REFERENCES


1. Gados, R. G., "Comparison of FAA Integrated Noise Model Flight Profiles with Observed Altitudes and Velocities at Dulles Airport," The MITRE Corporation MTR-80W00119, March 1980.

2. Federal Aviation Administration, "Noise Abatement Departure Profile for Turbojet Powered Aircraft Weighing over 75,000 Pounds," Advisory Circular 91-53, October 1978.

3. Reinsch, C. H., "Smoothing by Spline Functions," Numerische Mathematik, 1967, 10, 177-183.

MITRE Department
and Project Approval: Balraj G. Sokkappa

Dr. Balraj G. Sokkappa

DAT
FILM